Effects of hypercapnia and oscillation versus static mean exposure on the thermal performance of the model sea urchin, *Strongylocentrotus purpuratus*

*Spindel,N.B.; Munstermann,M.; Karelitz,S.; Galloway,A.W.E.; Schram,J.B.; Ferraro, R.; Collicutt,B.; Rolheiser,K.; Gimenez,I.; Cronmiller,E.; Foss,M.; Mahara,N.; Evans,W.; Swezey,D.S.; Rogers-Bennett,L.; Okamoto,D.K.

Nathan B. Spindel

nspindel@bio.fsu.edu

Florida State University

Gratitude

Territorial acknowledgements:

- Haida Nation
- We Wai Kai Nation
- We Wai Kum Nation
- Ucluelet Nation

Nathan B. Spindel - nspindel@bio.fsu.edu

Major Professor:

Dr. Dan Okamoto

Supervisory Committee:

Dr. Don Levitan

Dr. Sophie McCoy

Dr. Markus Huettel

Dr. Jonathan Dennis

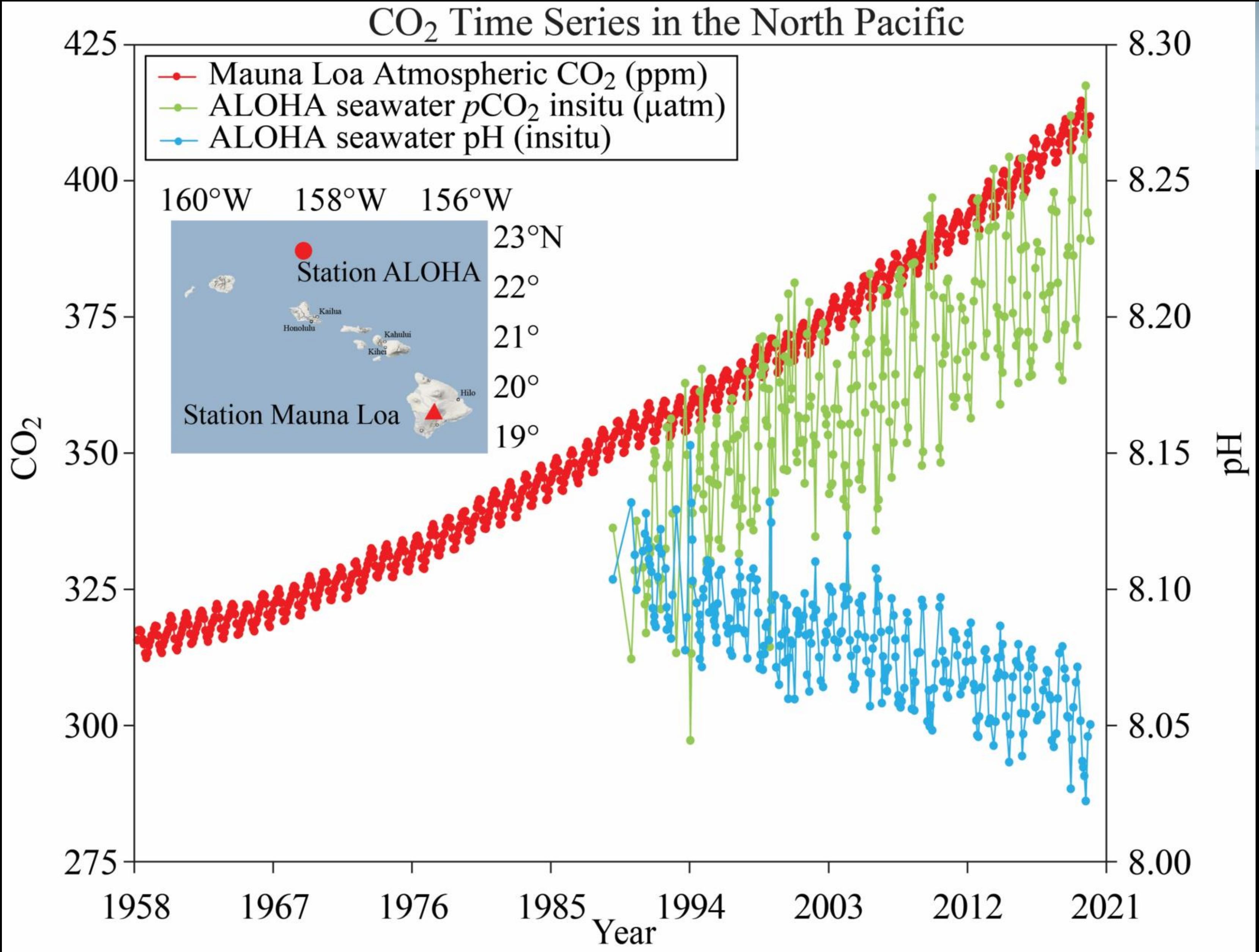
Dr. Scott Burgess

Okamoto Lab:

Maya Munstermann, Sam Karelitz, Christian Commander, Matthew Schumm, Rachele Ferraro, Diana Lopez

Undergraduates:

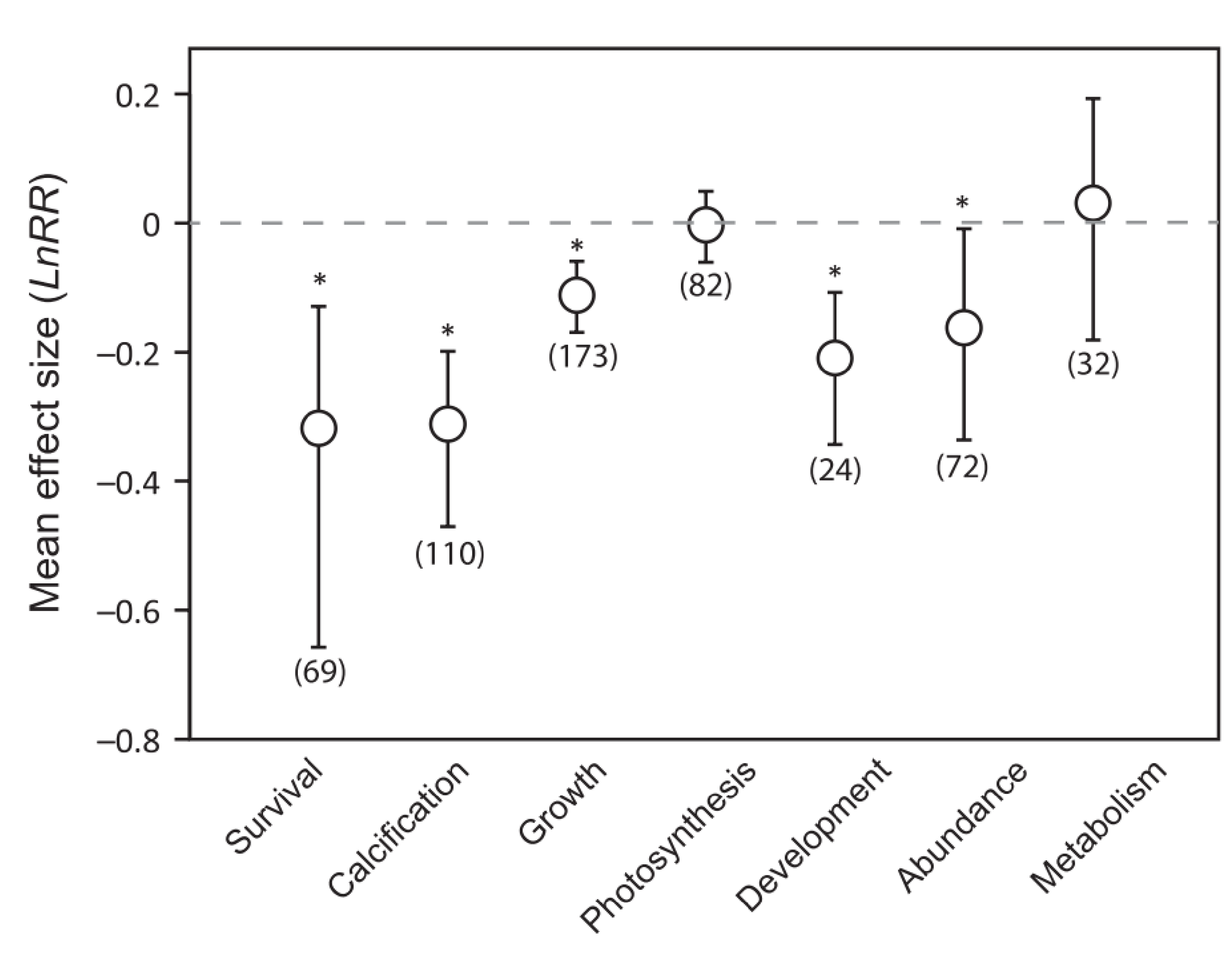
Maria Nunez, Sofia Yudin-Perez, Isaiah Vasquez, Kara Thornton, Anthony Cappellino, Trevor Alspach,



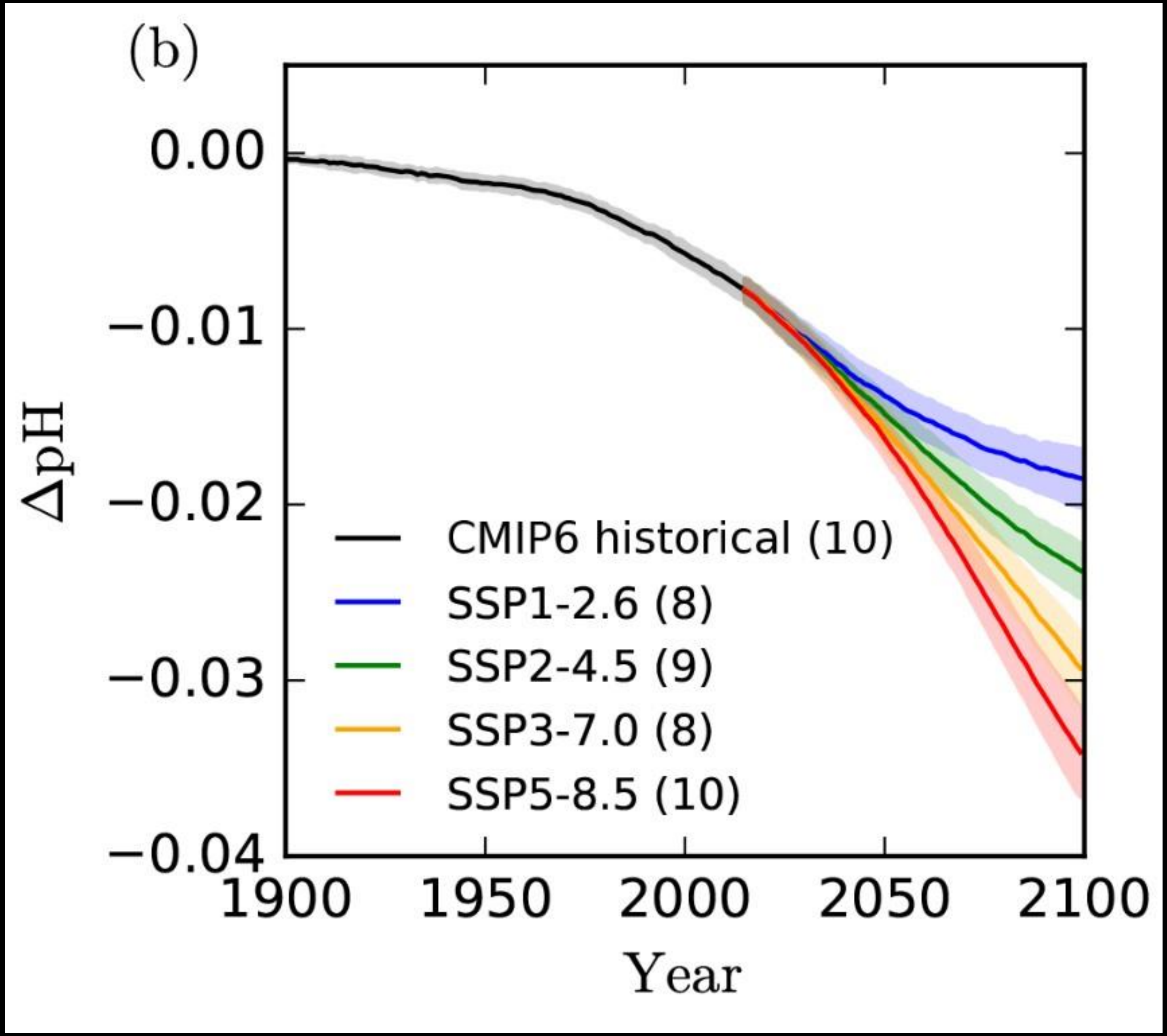
Data: Mauna Loa (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/hot-dogs/bextraction.html)
ALOHA pH & pCO_2 are calculated at in-situ temperature from DIC & TA (measured from samples collected on Hawaii Ocean Times-series (HOT) cruises) using co2sys (Pelletier, v25b06) with constants: Lueker et al. 2000, KSO4: Dickson, Total boron: Lee et al. 2010, & KF: seacarb

Biological implications

“future” high CO_2 (0.5 less than global mean surface pH) generally decreases performance.



Kroeker, K. J. et al. 2013
Global Change Biology

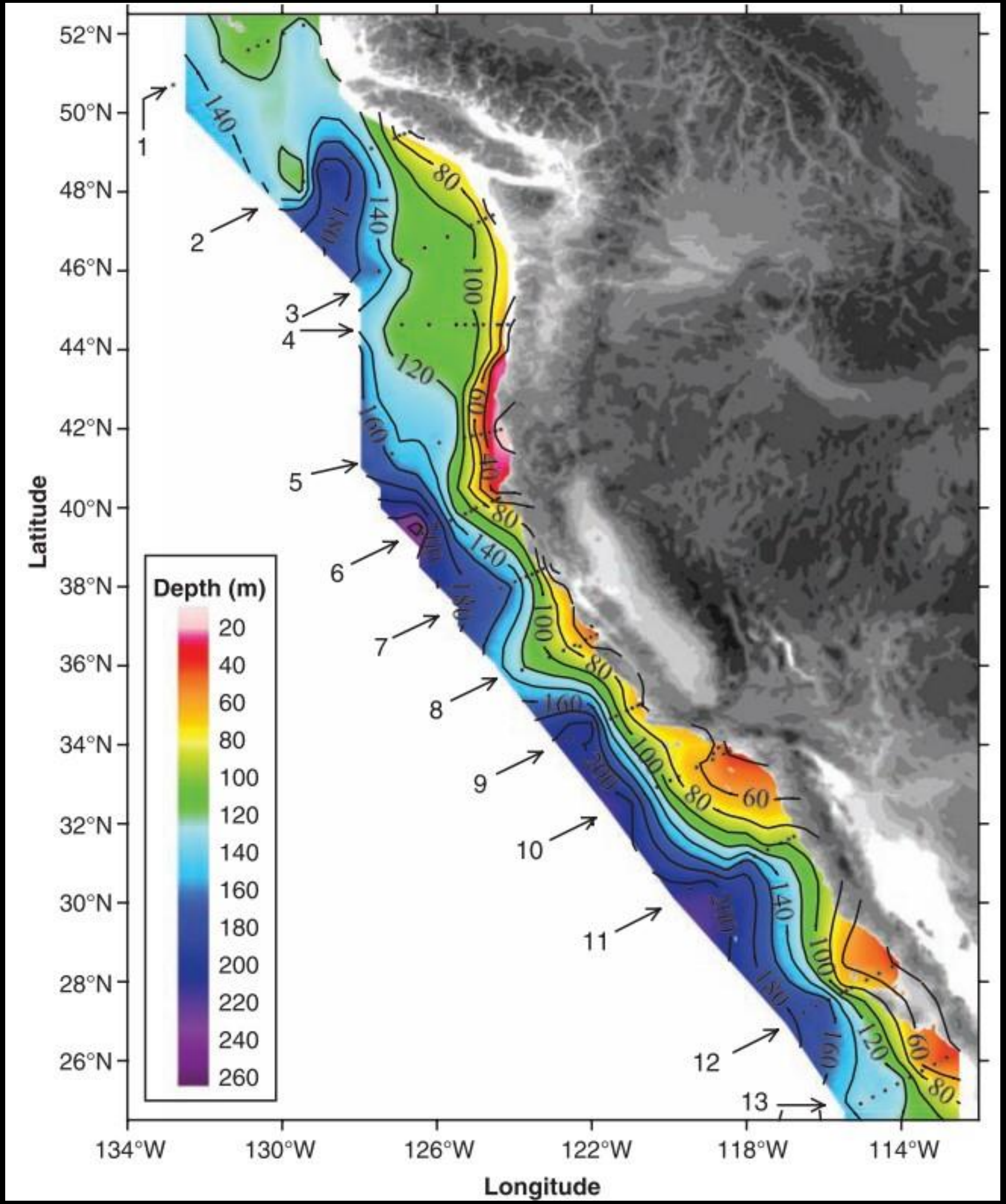


**Global mean surface seawater!*

Kwiatkowski et al. 2020
Biogeosciences

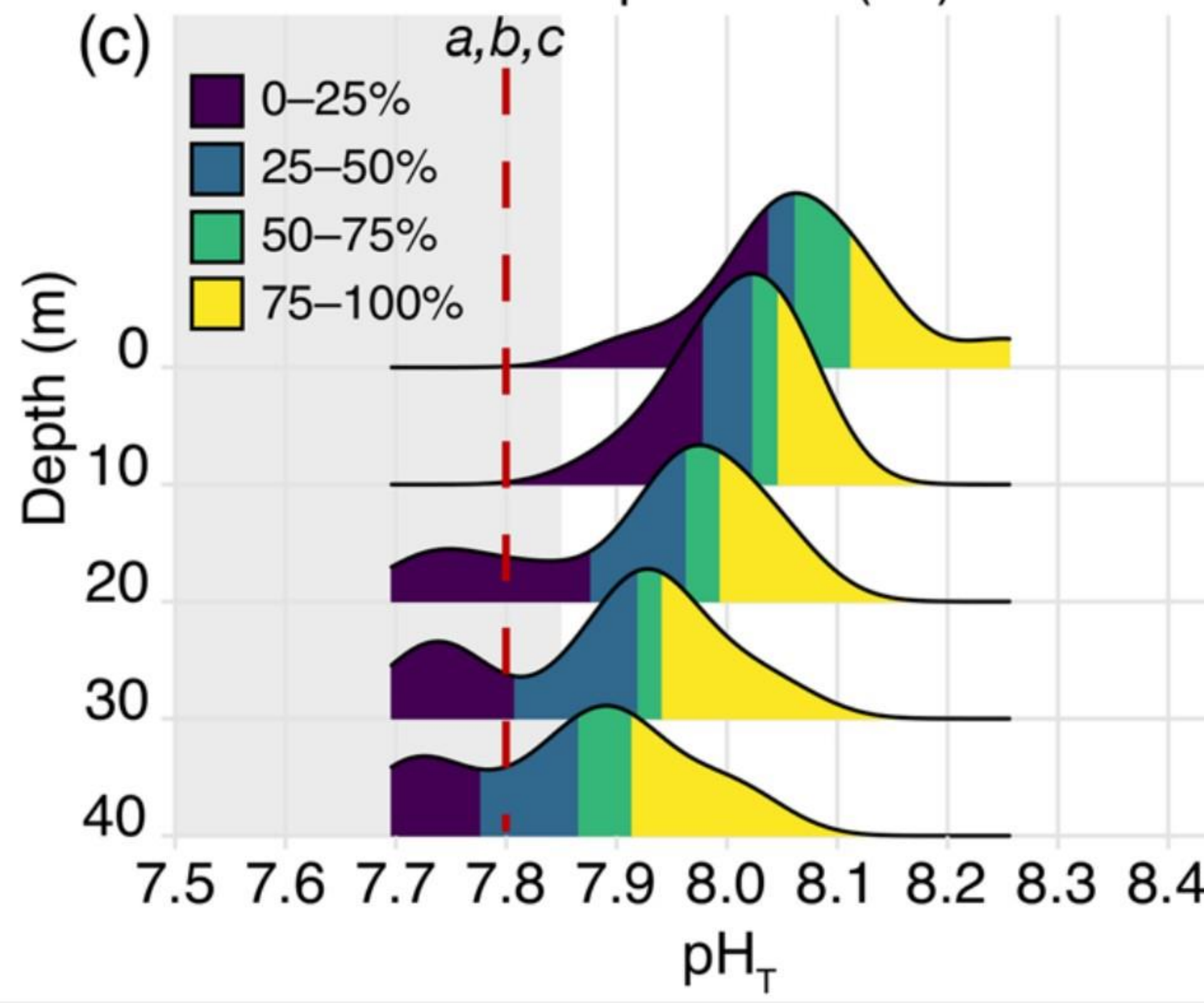
However…

Corrosive conditions (i.e., high pCO_2, aragonite saturation < 1.0; pH < 7.75) regularly reaches ecologically relevant depths in the nearshore, particularly in upwelling zones



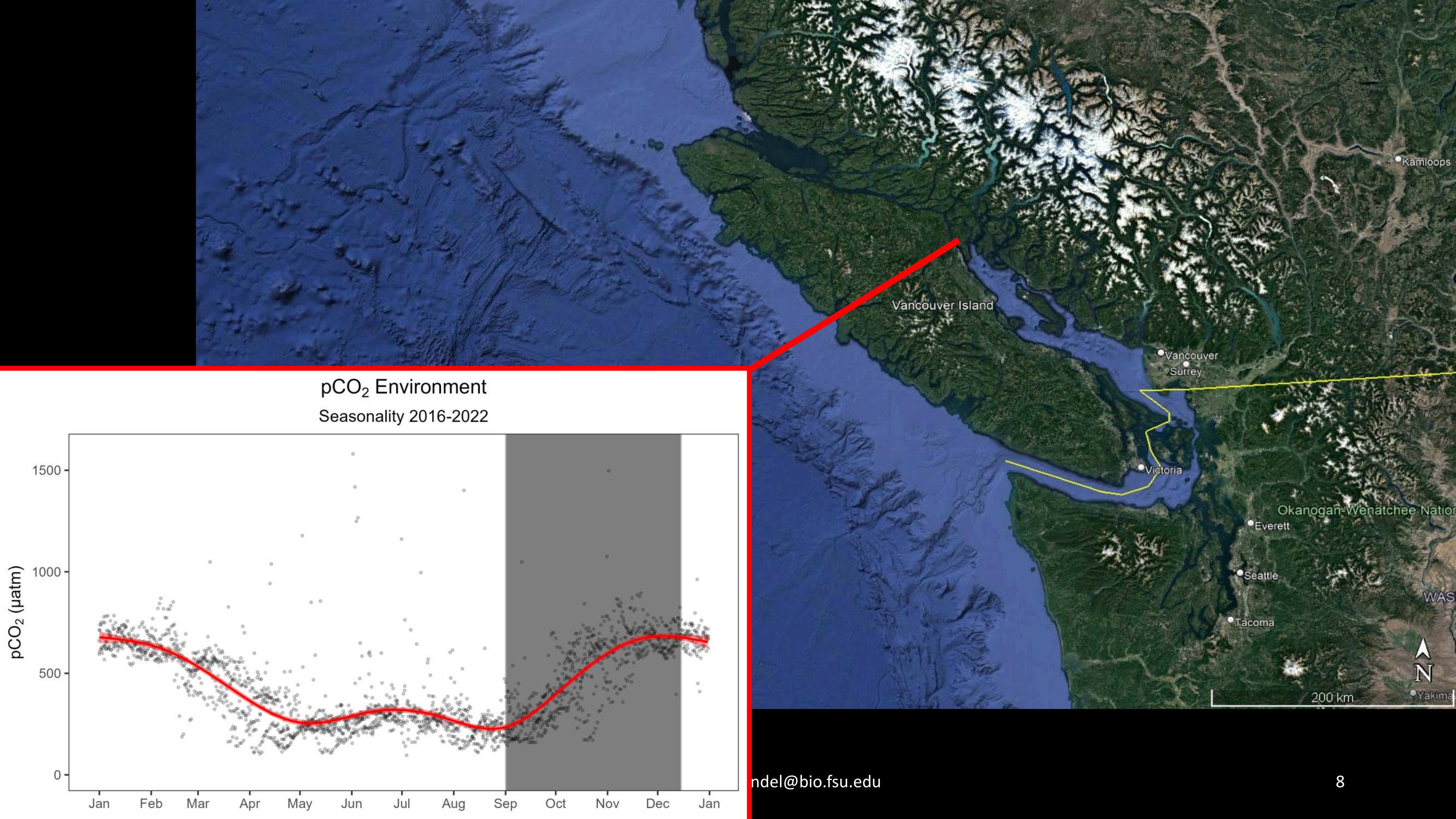
Feely et al. 2008 Science

"future" corrosive conditions occur in nearshore subtidal *now*

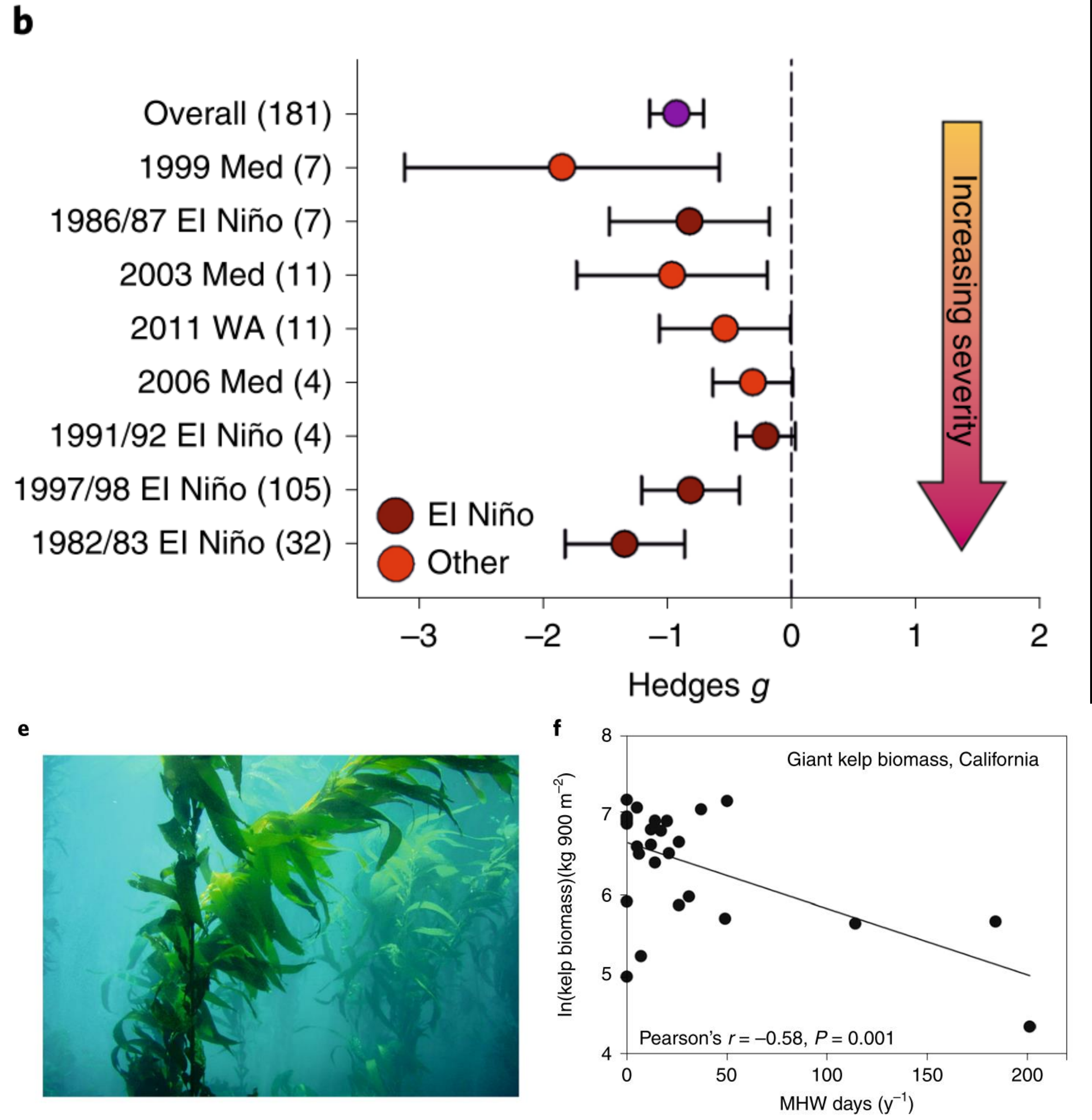


Kekuewa et al. 2022
Scientific Reports

IPCC SSP-5-8.5 mid-century mean oceanic pHT = 7.85 for SSP-5-8.5


Kamloops
Vancouver Island
Vancouver
Surrey
Victoria
Everett
Seattle
Tacoma
N
200 km
pCO_2 Environment
Seasonality 2016-2022
pCO_2 (µatm)
1500
1000
500
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

- **<u>Ocean warming</u>** is punctuated by marine heat waves, threatening biodiversity and biomass loss of foundation species

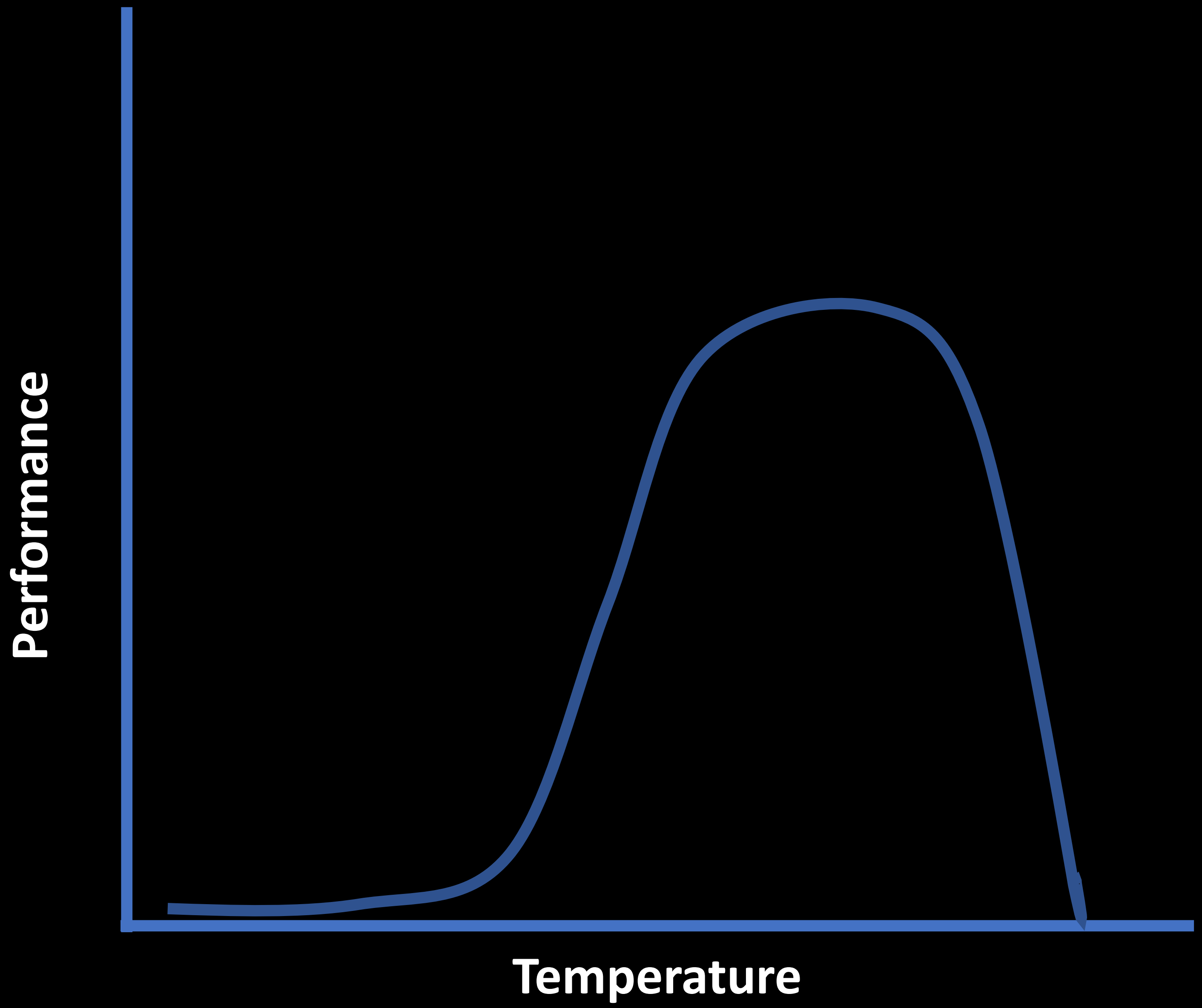


Smale, D. A. et al. (2019) Nature Climate Change

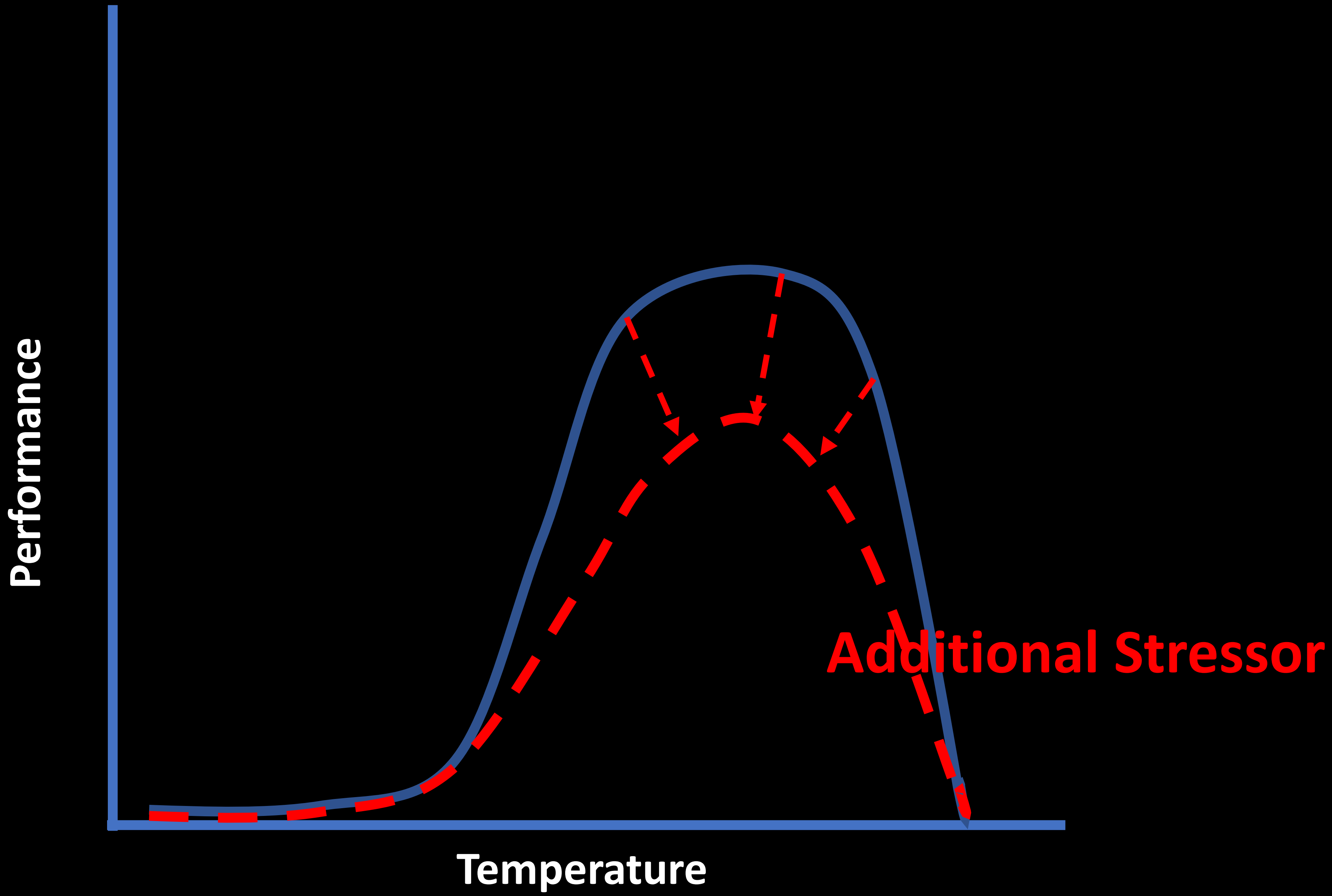
Questions

1. How does contemporary high CO2 affect thermal performance?
2. Do constant thermal regimes impose the same effects on performance as dynamic regimes with shared mean values?

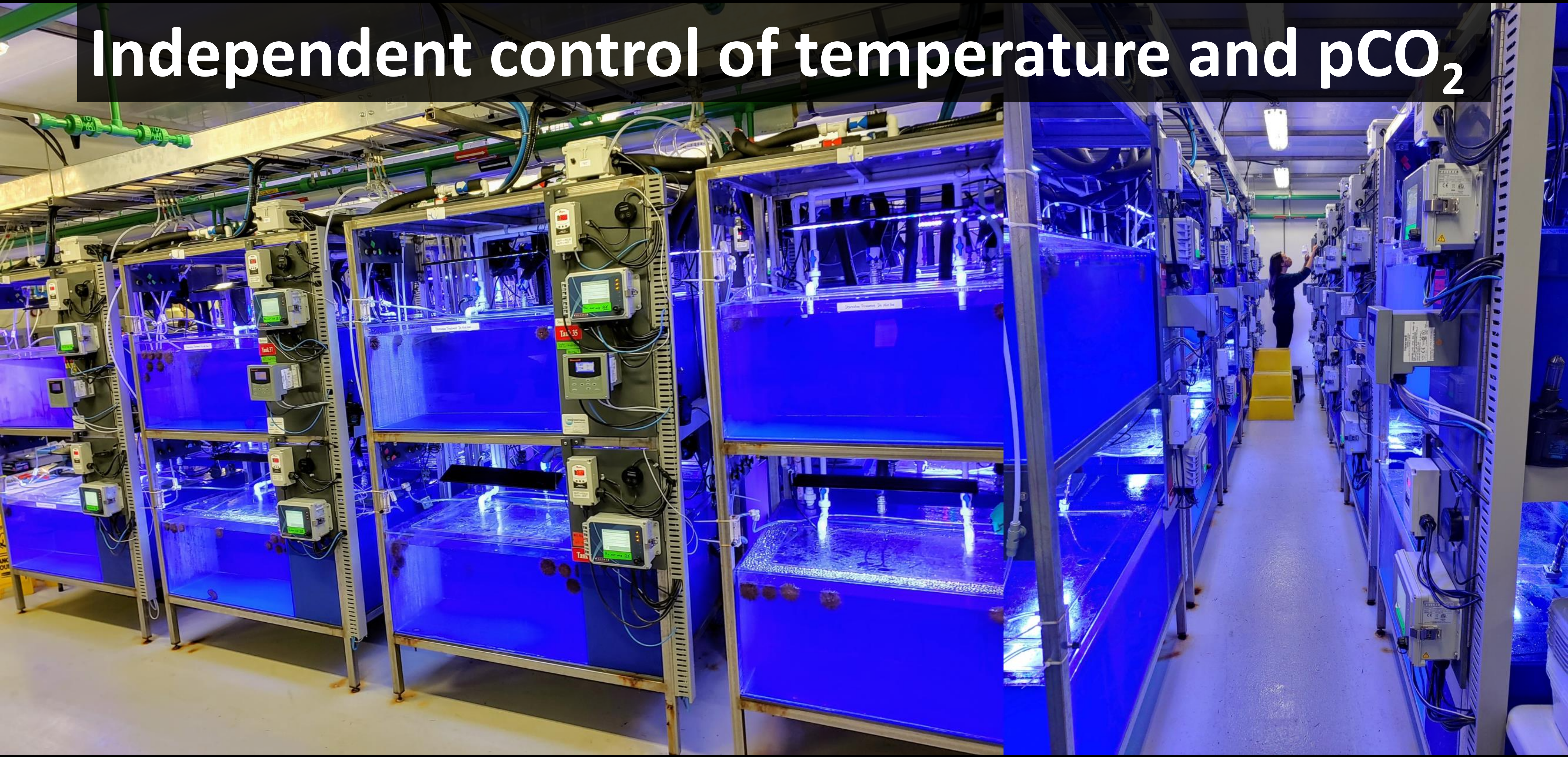
Thermal Performance Curve



Thermal Performance Curve



Independent control of temperature and pCO_2



Treatments

Temperature (℃)	Constant or Dynamic	pCO_2 (µatm)	Number of tanks
10	Constant	600	2
10	Constant	1200	2
13	Constant	600	2
13	Constant	1200	2
16	Constant	600	2
16	Constant	1200	2
17	Constant	600	2
17	Constant	1200	2
18	Constant	600	2
18	Constant	1200	2
20	Constant	600	2
20	Constant	1200	2
El Niño (21-18)	Dynamic	600	4
La Niña (18-14)	Dynamic	600	4

15 animals per tank x 32 tanks = 480 animals

(mean test diameter = 51 mm, range = 25-69 mm)

Fed 2x per week throughout using algal pellets for sea urchin aquaculture

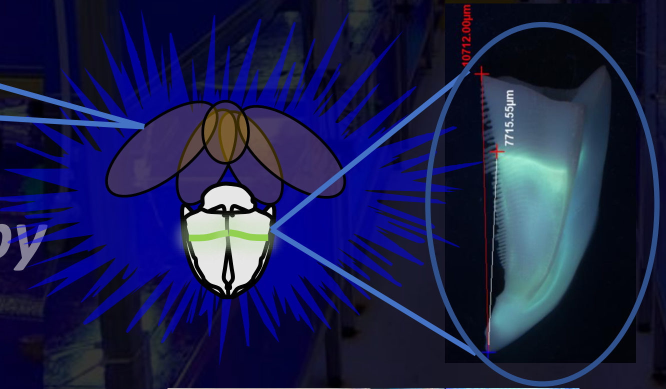
Responses – Energetic Profile

Metabolic rate – *respirometry*

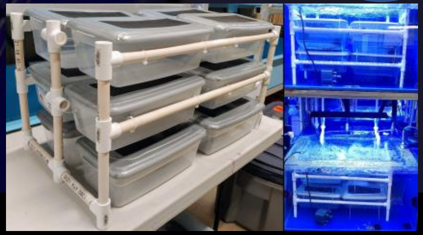
Per capita consumption rate – *replicated feeding trials*

Gonadal growth – *dissection*

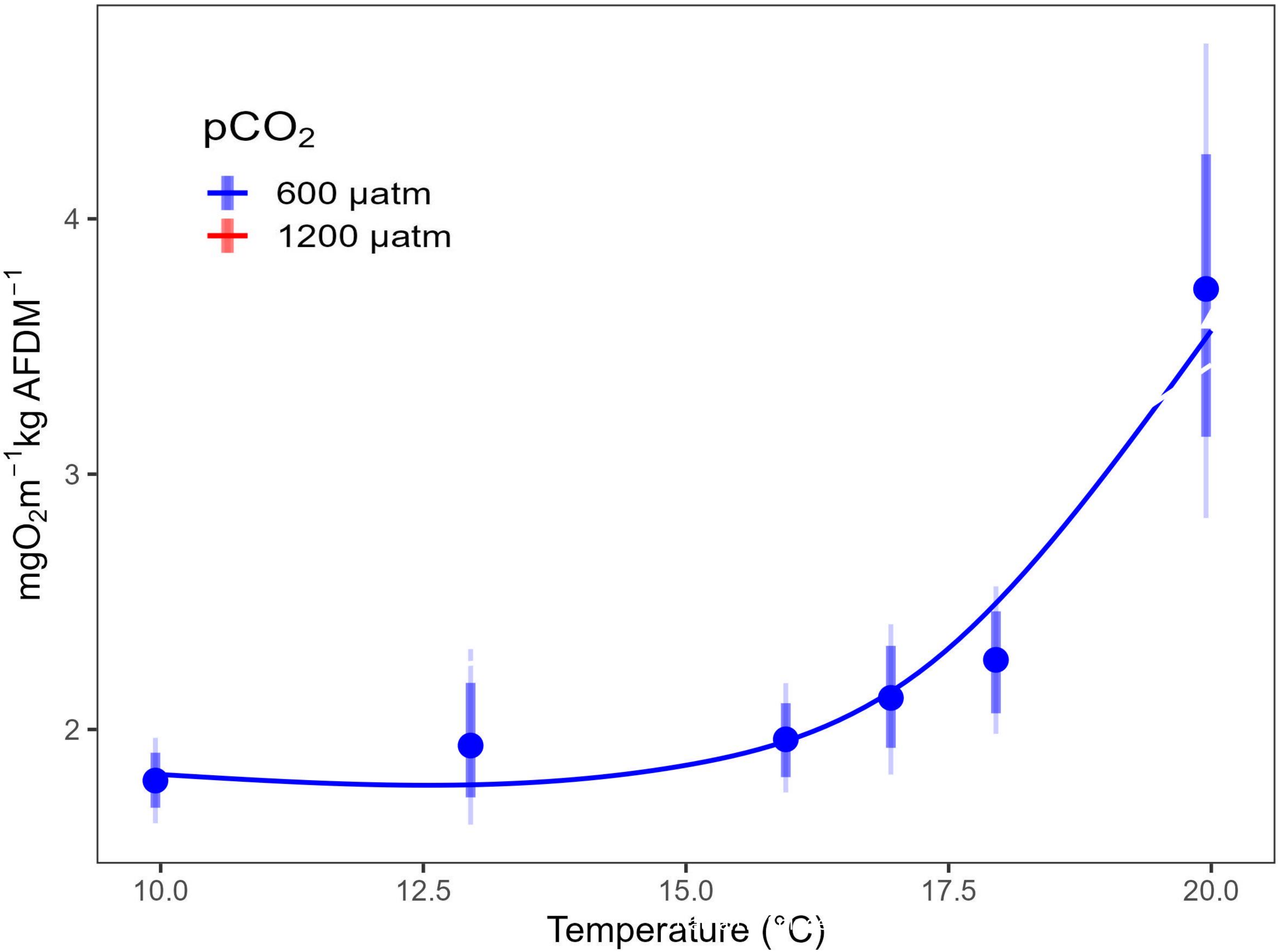
Structural growth – *tetracycline tagging + microscopy*



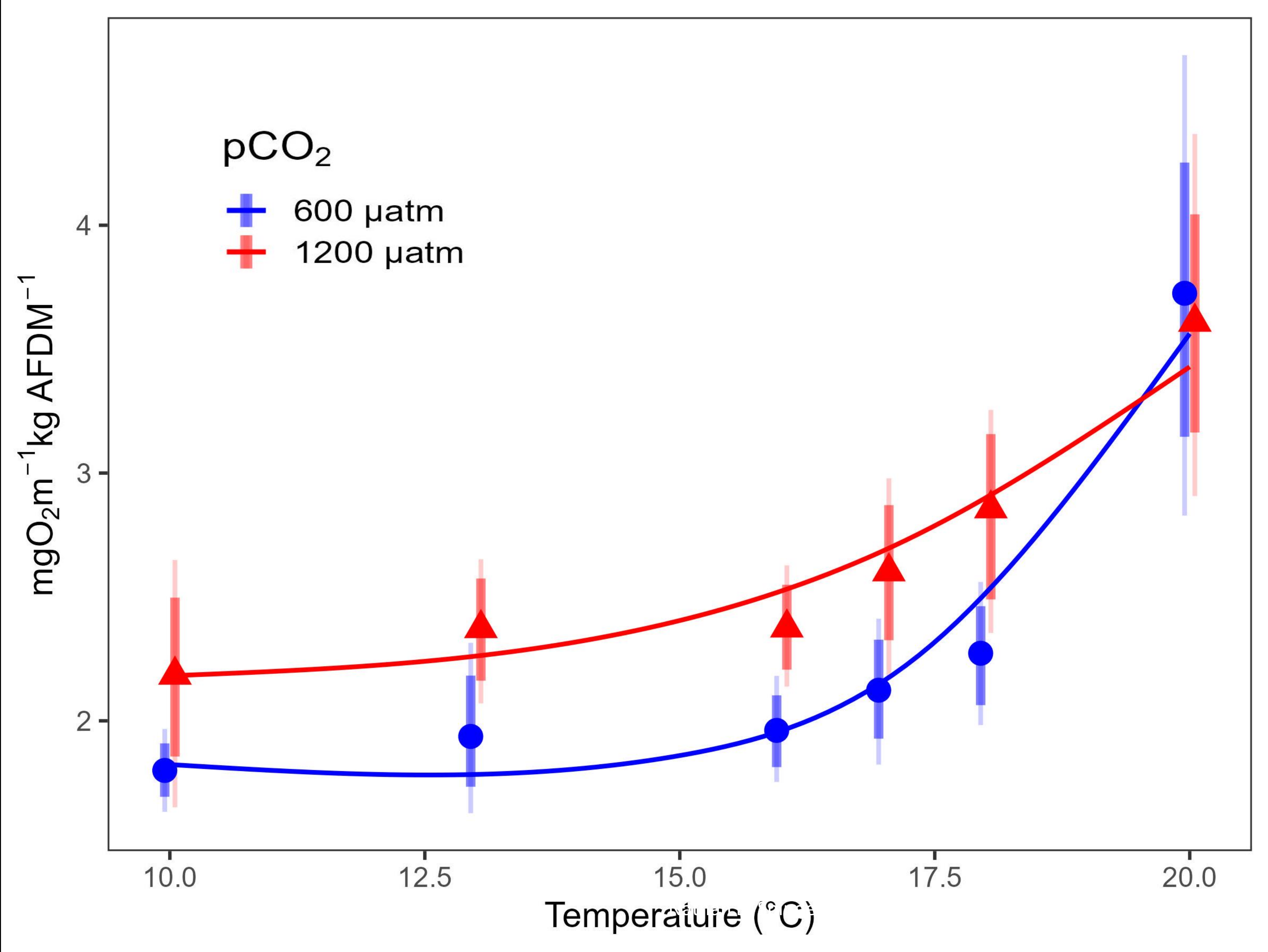
Efficiency – *ingestion/egestion, production/consumption*



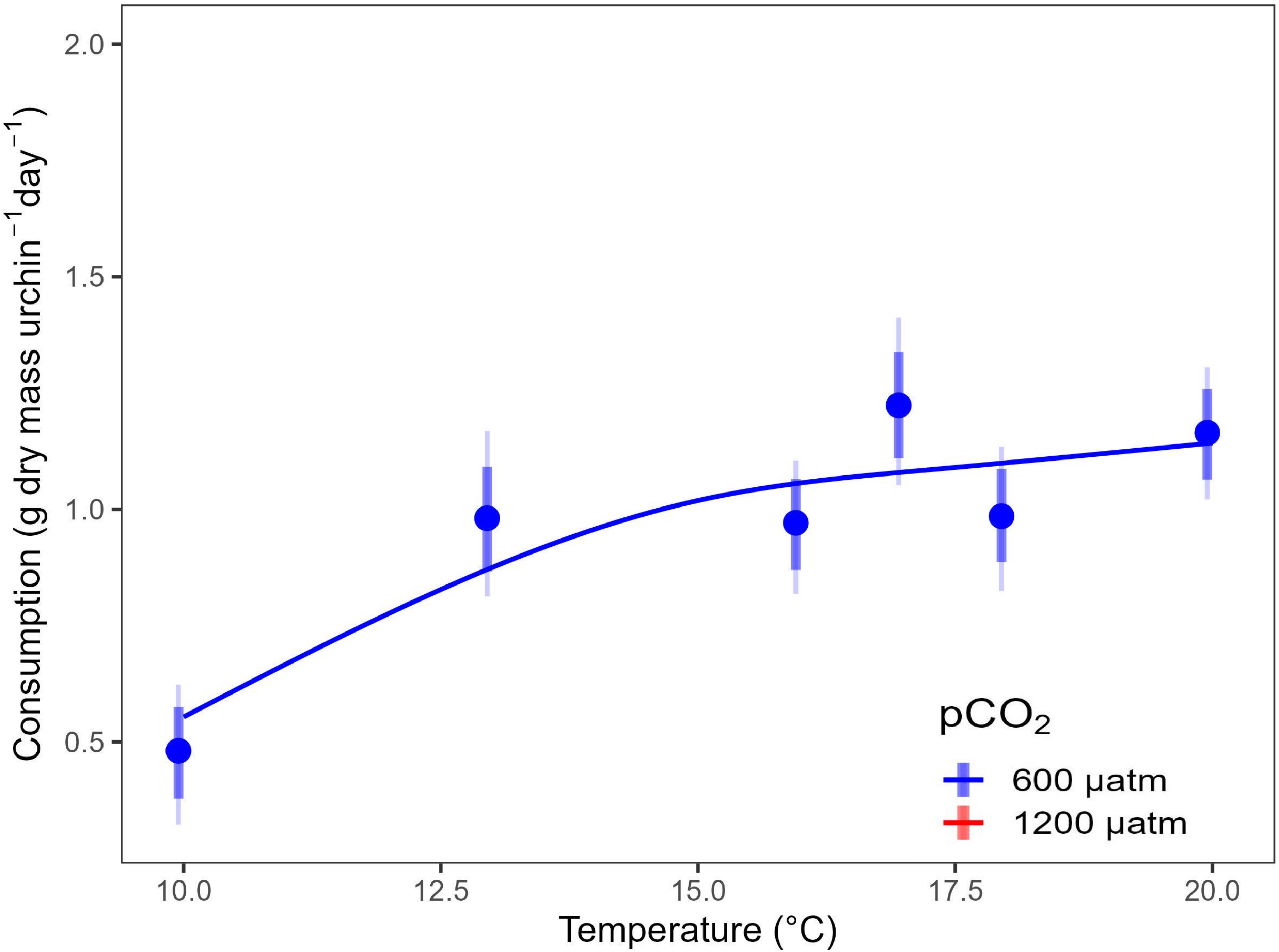
Nathan B. Spindel - nspindel@bio.fsu.edu



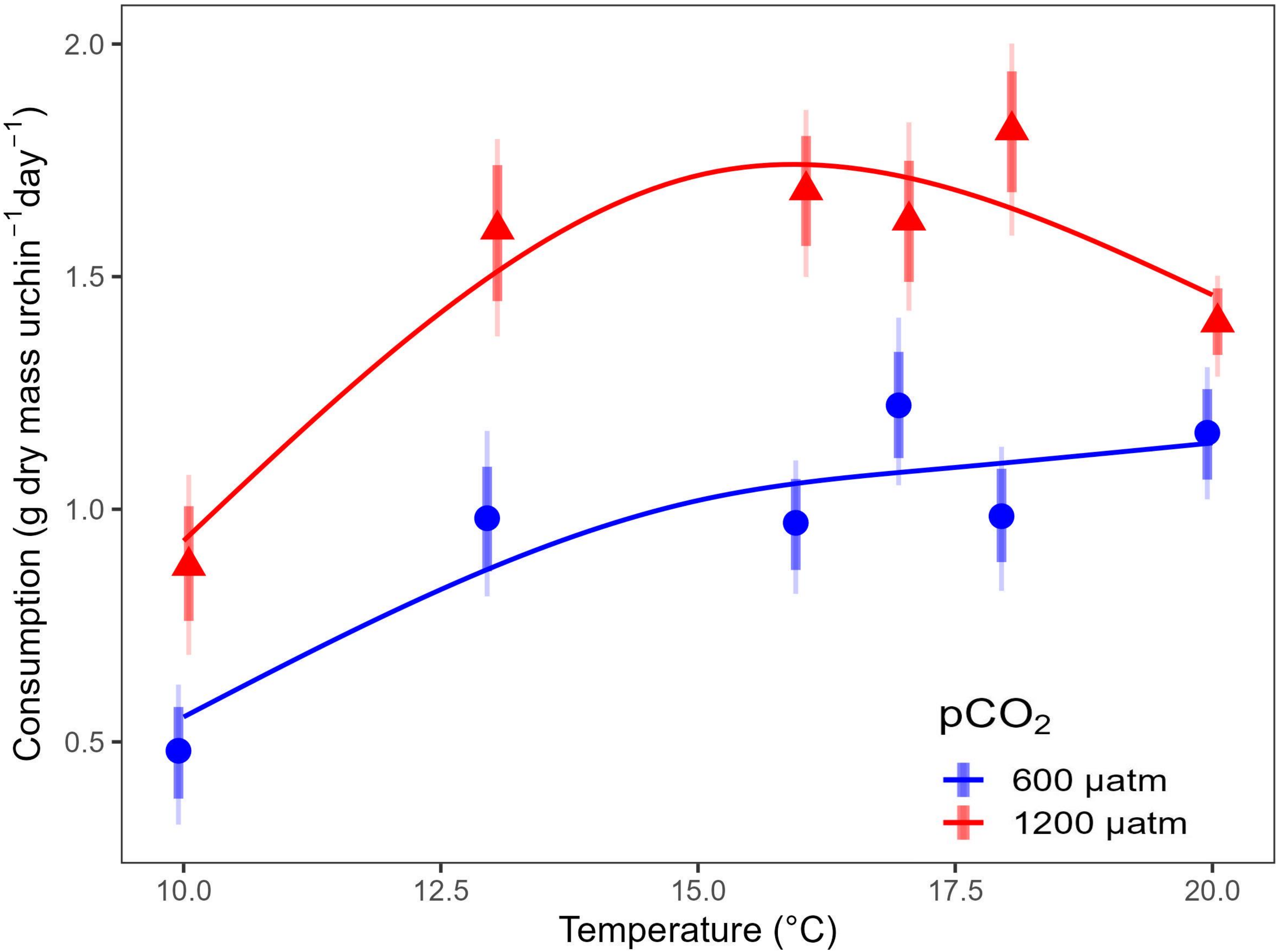
- ***At ambient pCO_2,*** **exponential increase in metabolic rate with temperature**



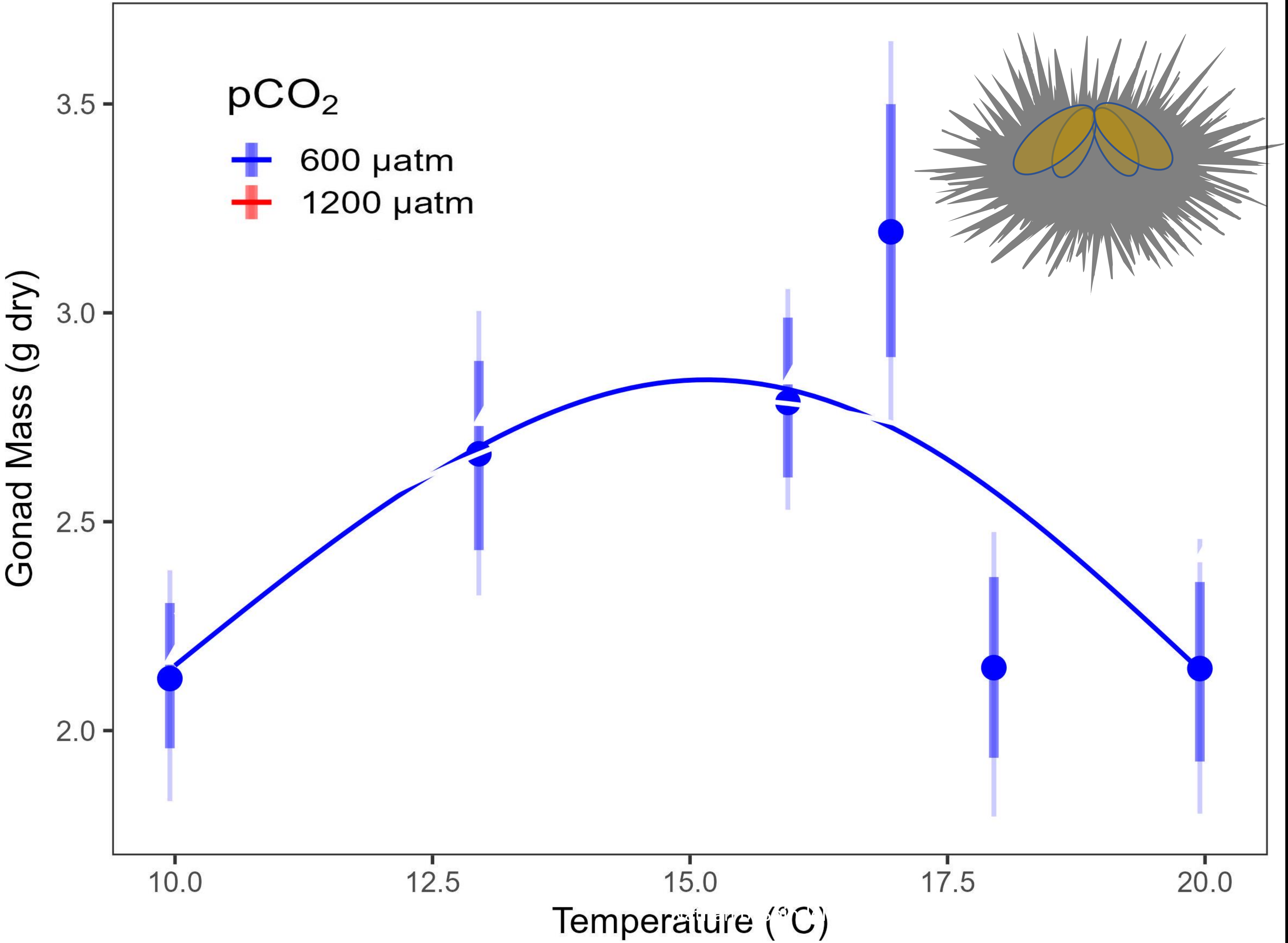
- ***Higher*** **metabolic rate in high CO_2, except for extreme 20 ℃**



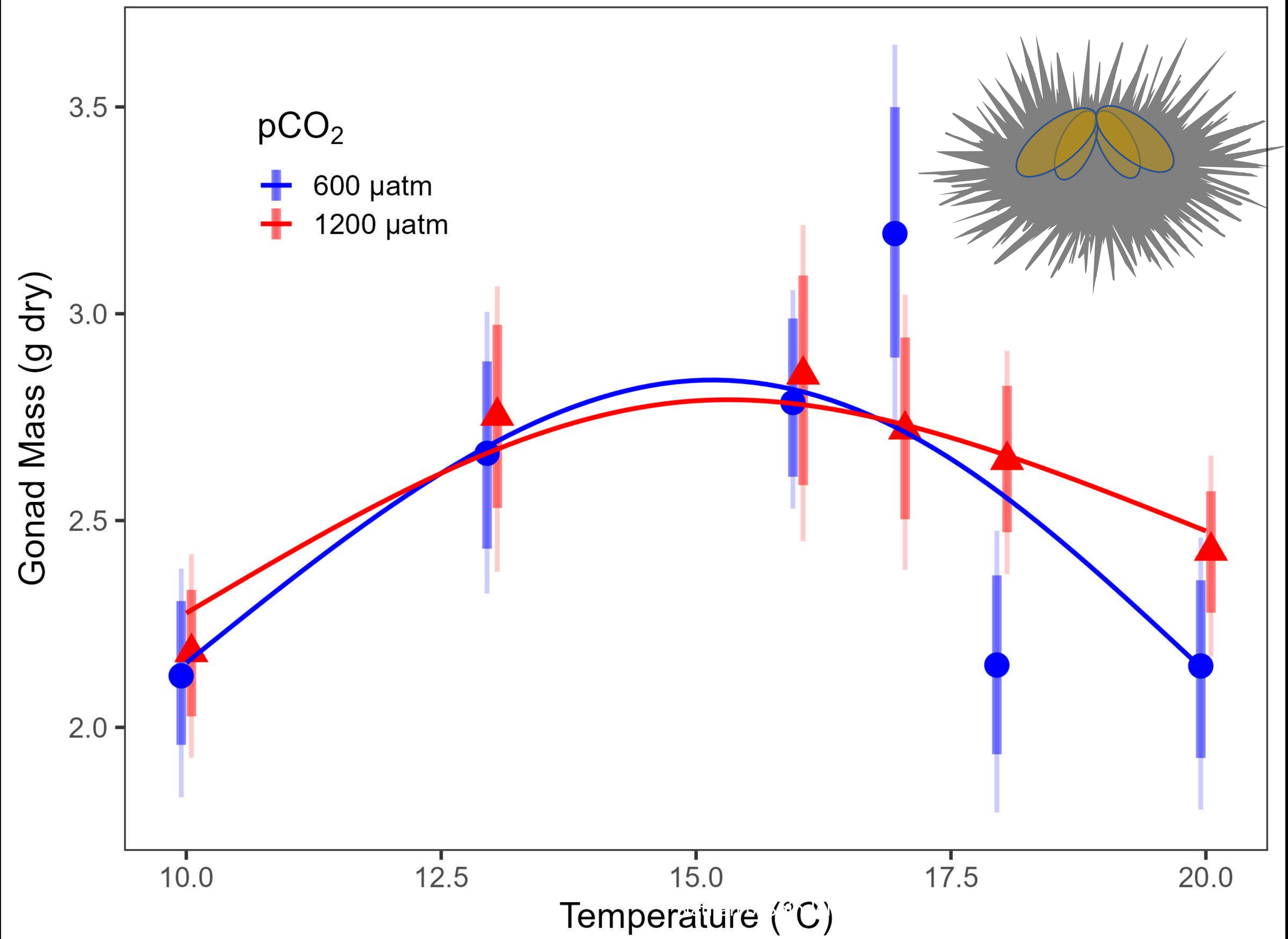
- ***At ambient pCO_2,*** **feeding increases with temperature**



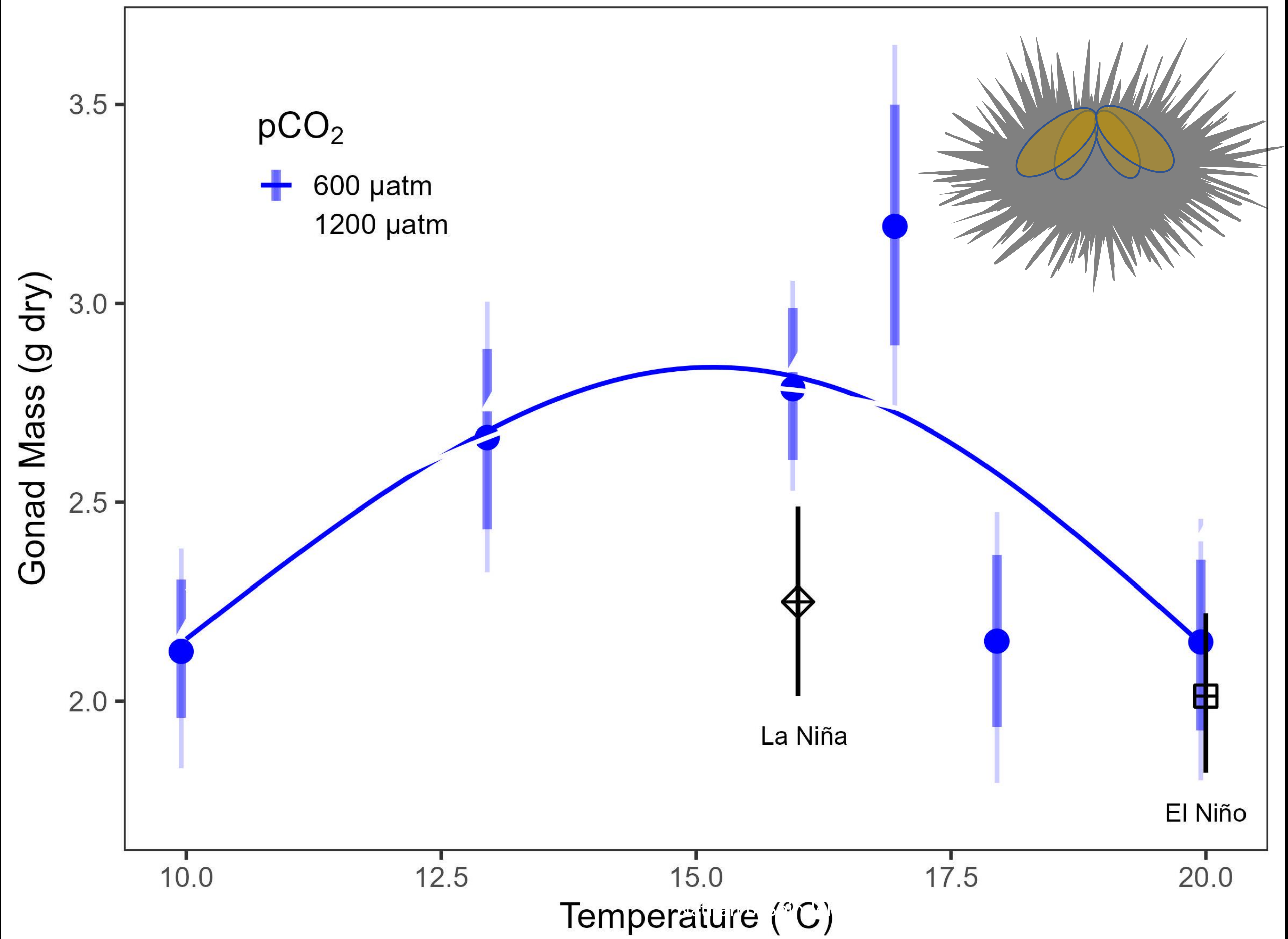
- ***Higher*** **per capita feeding under high CO_2**



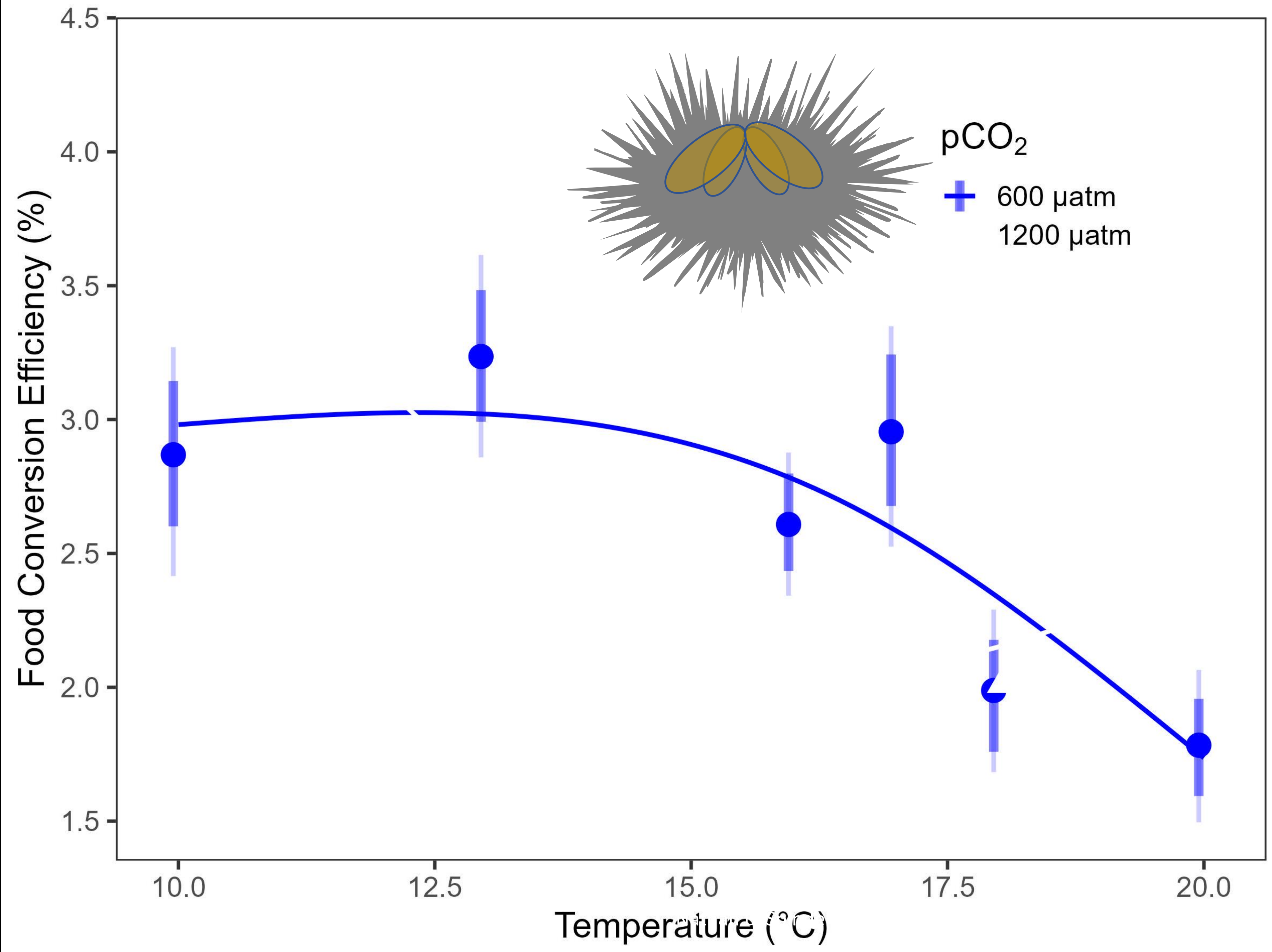
- ***At ambient pCO_2*, peak gonad production ~ 17 ℃**



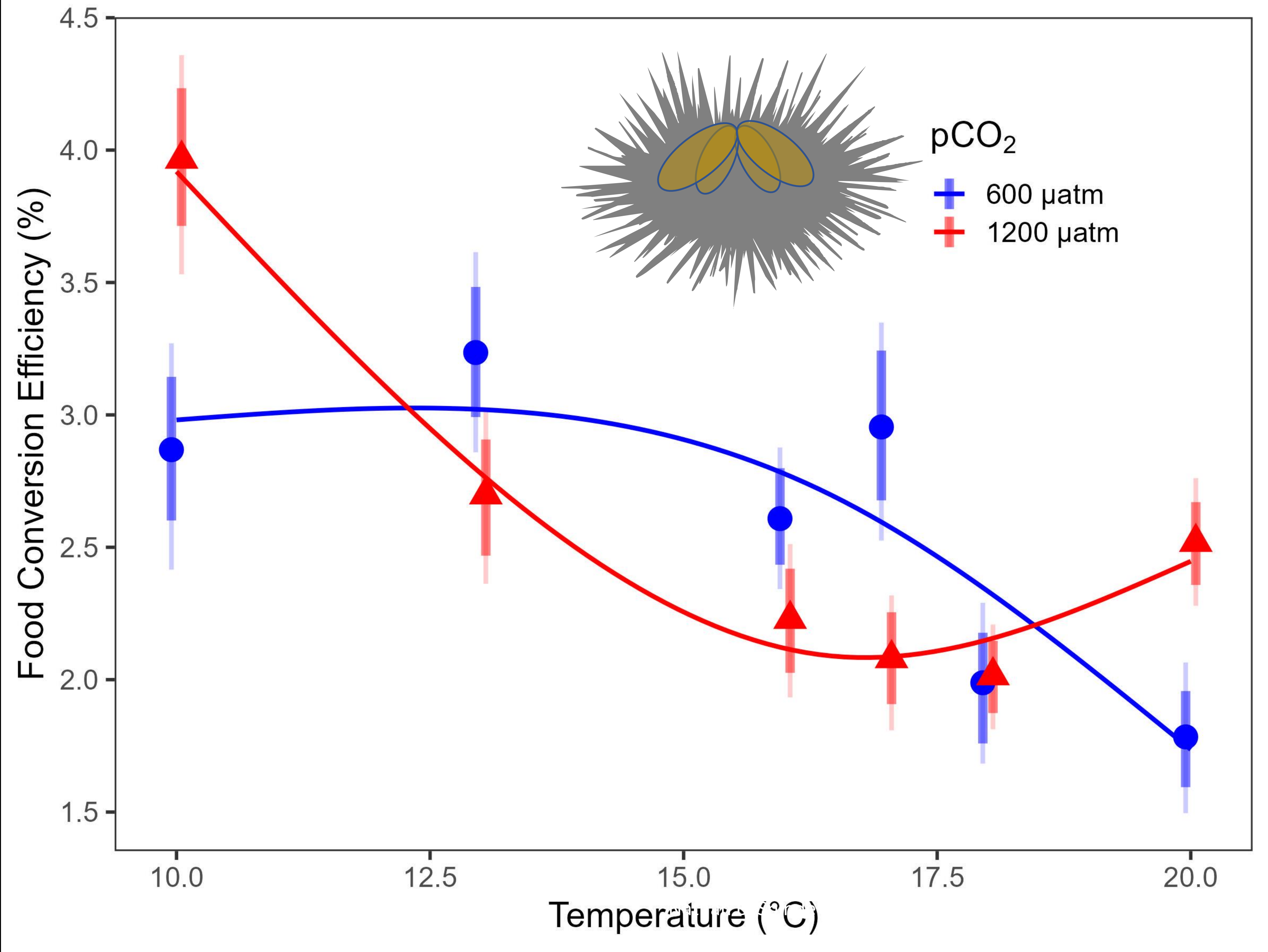
- ***Higher* gonadal production at temp > 17 ℃ under high CO_2**



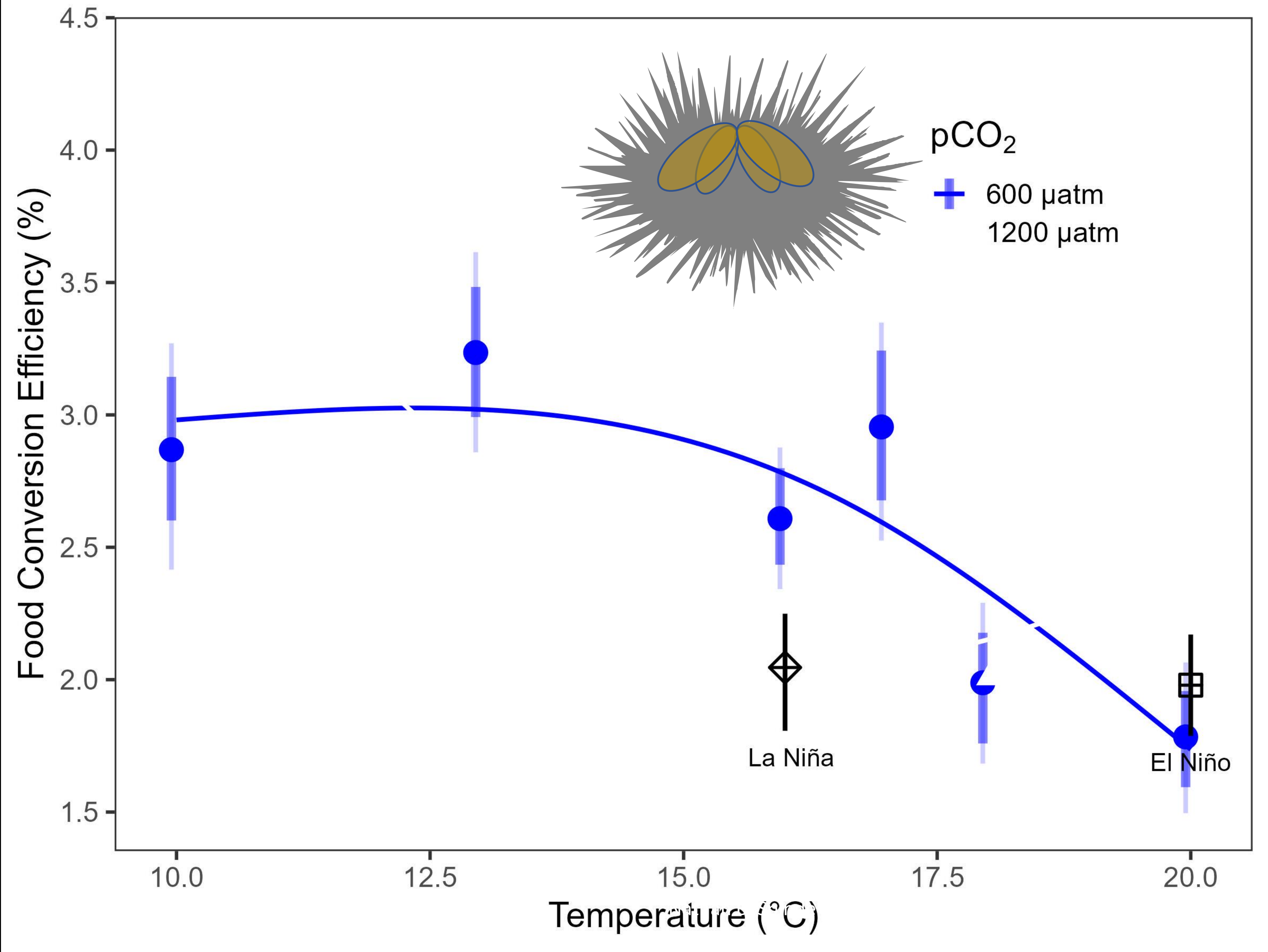
- ***Lower*** **gonadal production in La Niña**



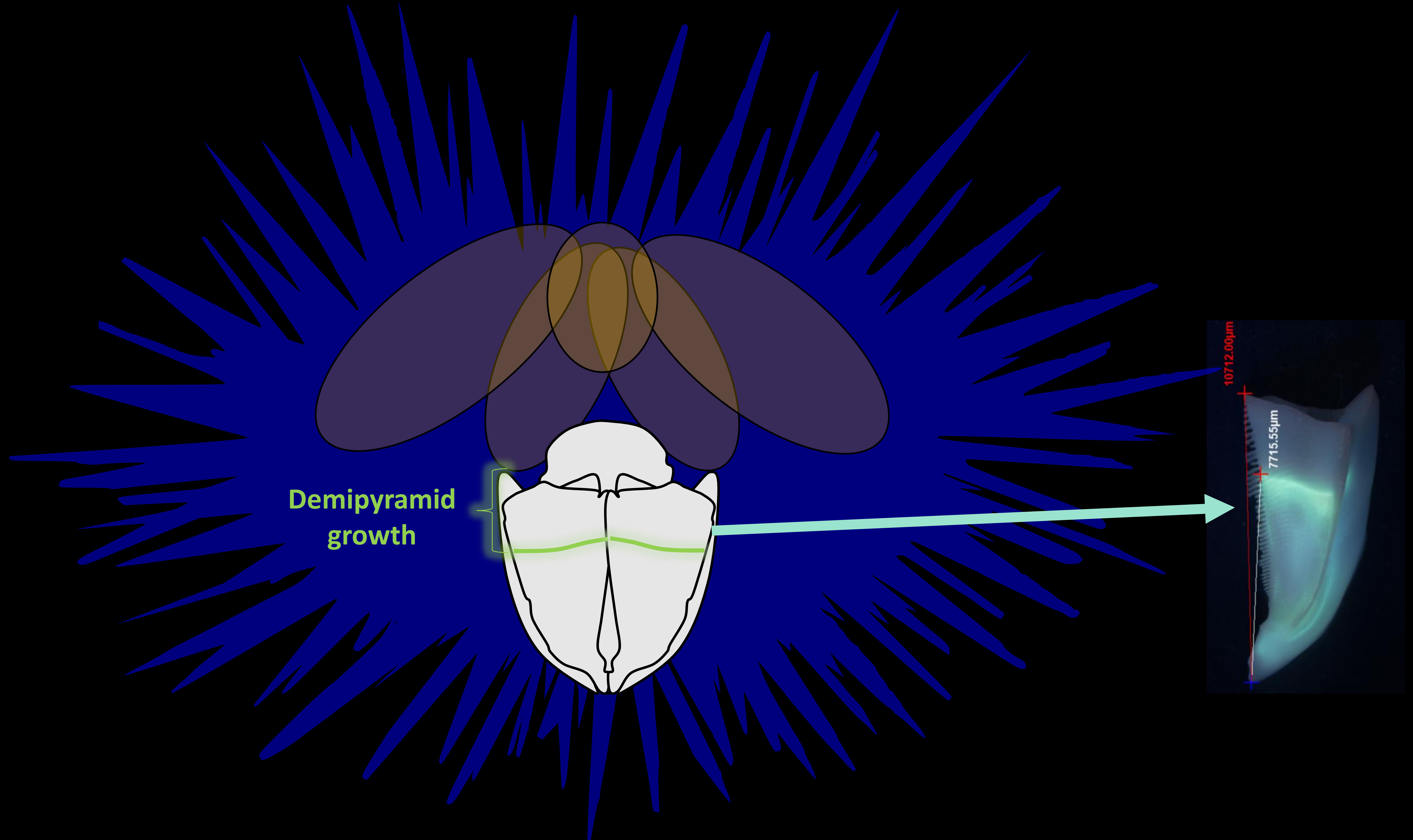
- ***At ambient pCO_2*, food conversion efficiency declines with temperature**

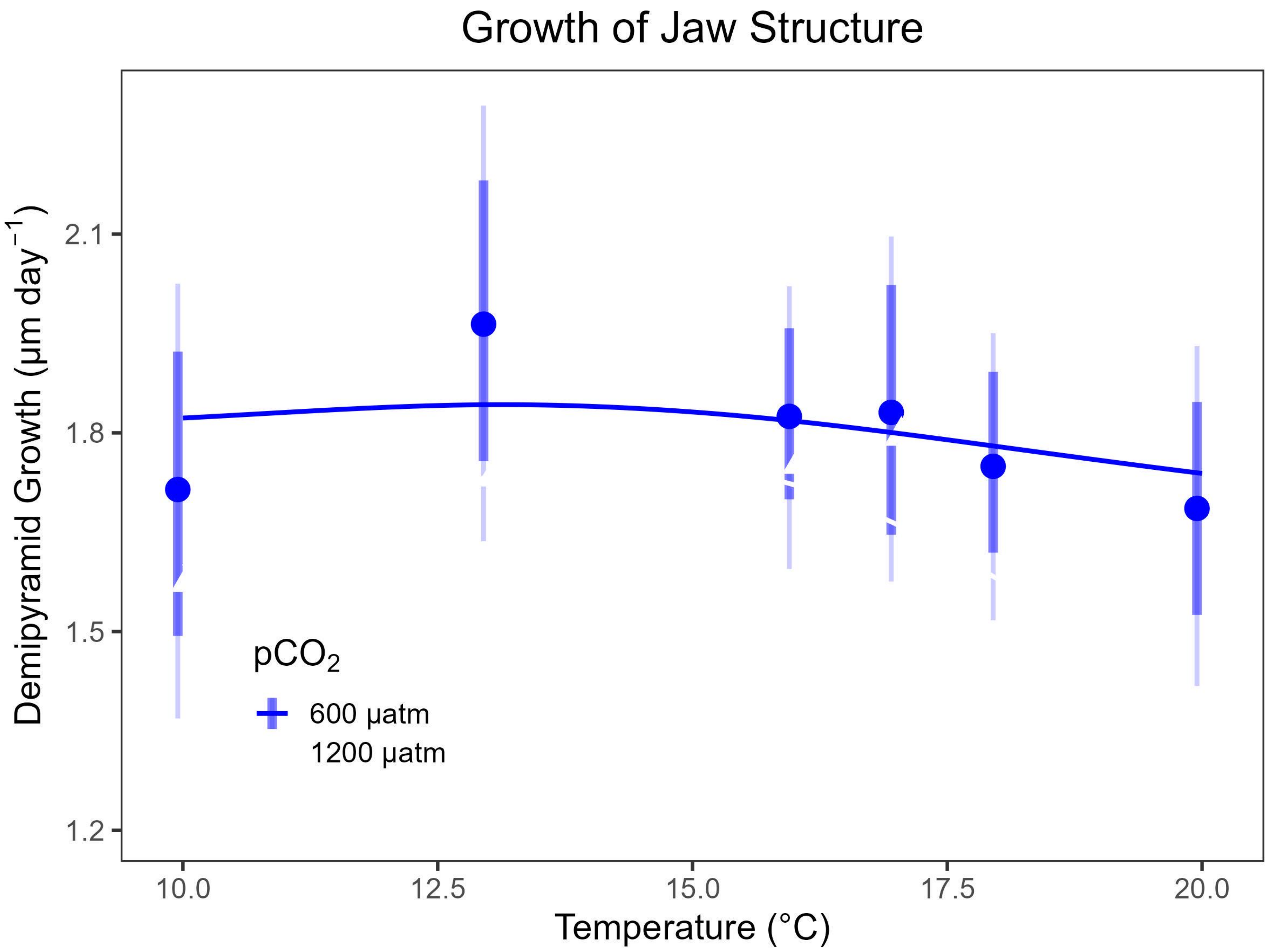


- ***At high pCO_2, Lower*** **efficiency near thermal optimum, but *higher* efficiency at extremes**

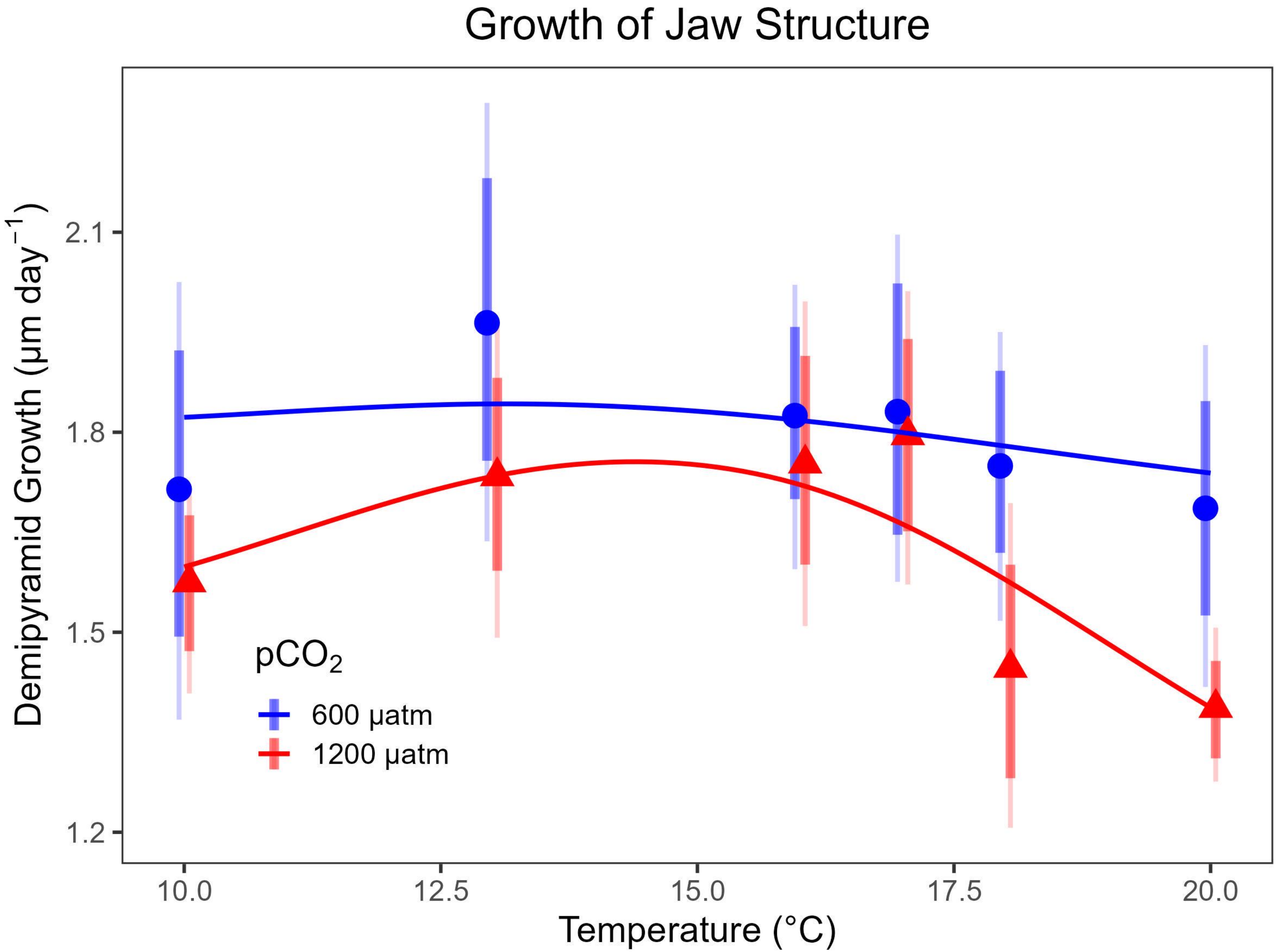


- ***At ambient pCO_2, lower*** **gonadal production efficiency in La Niña**

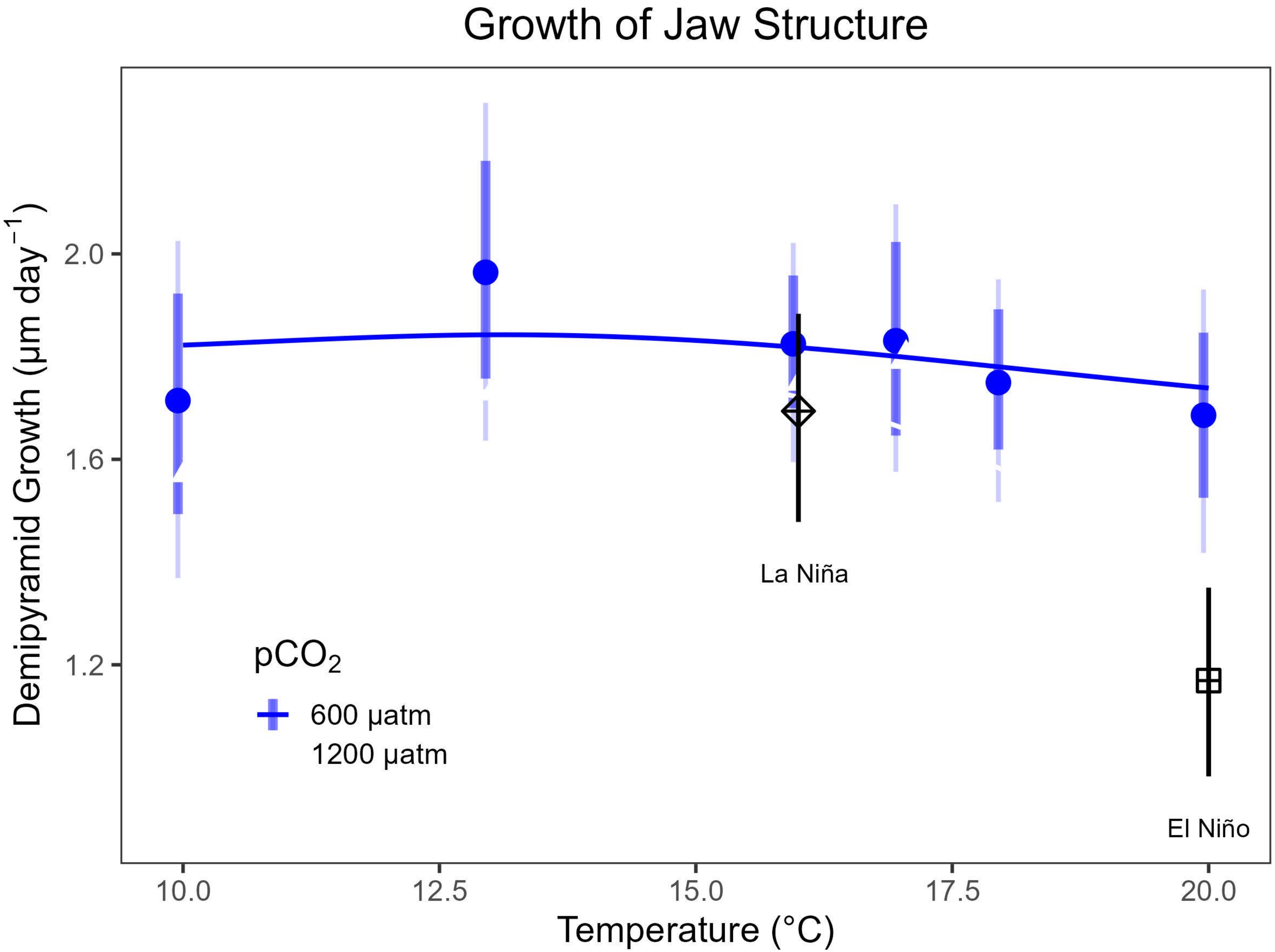

Demipyramid
growth
10712.00µm
7715.55µm



- ***At ambient CO2,* weak relationship between jaw growth and temperature**



- ***At high CO2, Lower*** **jaw growth, particularly at thermal extremes**



- ***At ambient CO2, Lower* jaw growth in El Niño**

Implications

- Barren state may increase in frequency/persistence under contemporary warming, more so in high pCO_2 contexts
  - Aggravating factors:
    - *Ocean acidification*
    - *Decline in nutritional quality of primary production (e.g., Lowman, H. E., et al. 2021 Oikos.*
  - Mitigating factors:
    - *High nutrients and pCO_2 stimulate algal growth, low temp -> decrease herbivore metabolism & feeding (e.g., Sellers, A. J., et al 2019 Global Ecol Biogeogr).*
- TPC's estimated with constant treatments may overestimate reproductive potential

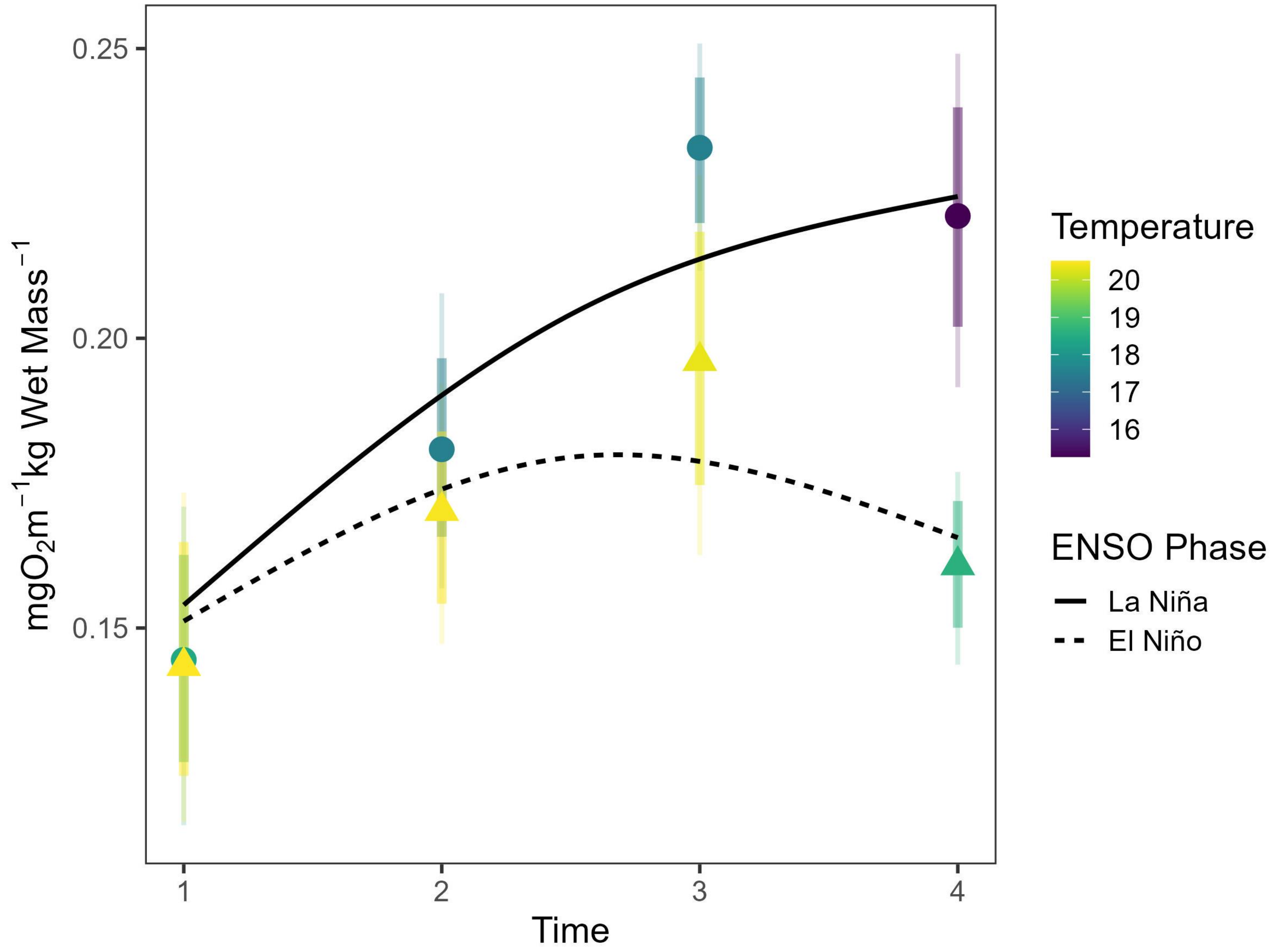
Future Directions

- **Multistressor experiments exposing *both food resource & consumer***
  - (e.g., Brown, M. B., Edwards, M. S. & Kim, K. Y. 2014 Algae).

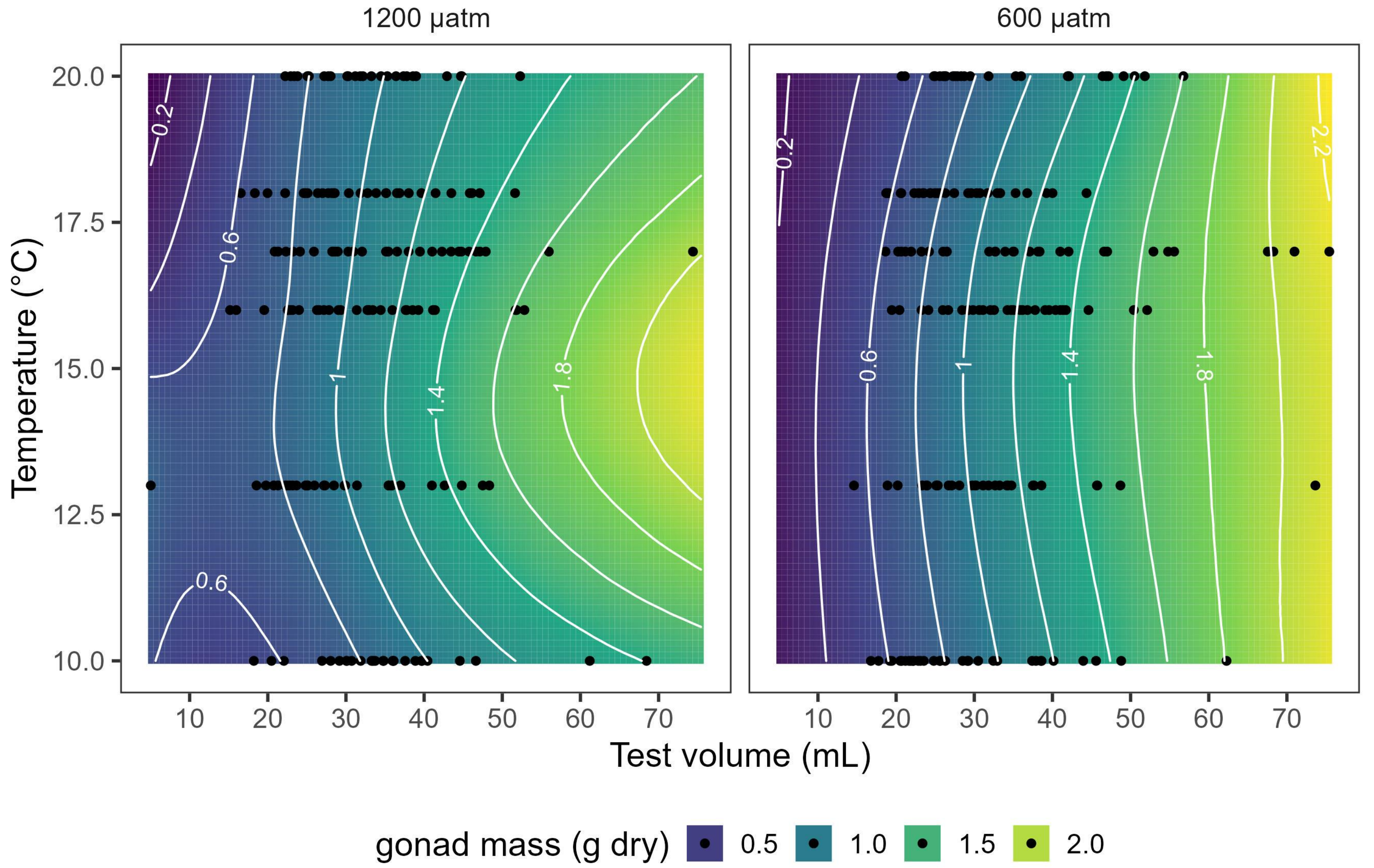
- **Process based model development for upscaling to population level herbivory**
  - (e.g., Arnould-Pétré, M., et al 2021 Ecological Modelling)

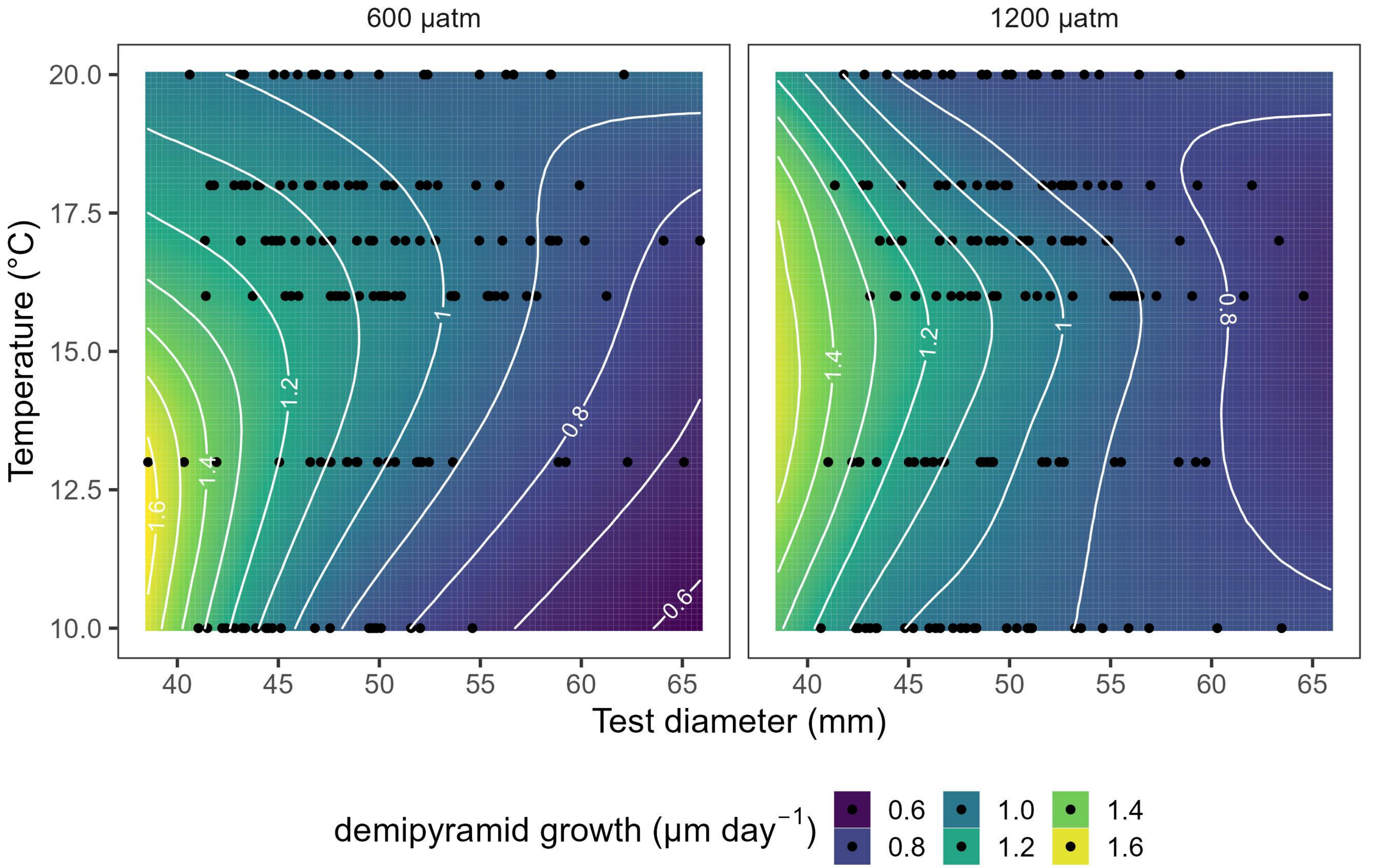

THANK YOU!
CONTACT:
Nathan B. Spindel
nspindel@bio.fsu.edu
PhD Candidate
Smithsonian Predoctoral Fellow
Florida State University
Take-homes:
High pCO2 + warming -> S. purpuratus eat more -> + barrens??
Constant vs dynamic -> overestimate reproductive potential

EXTRA SLIDES



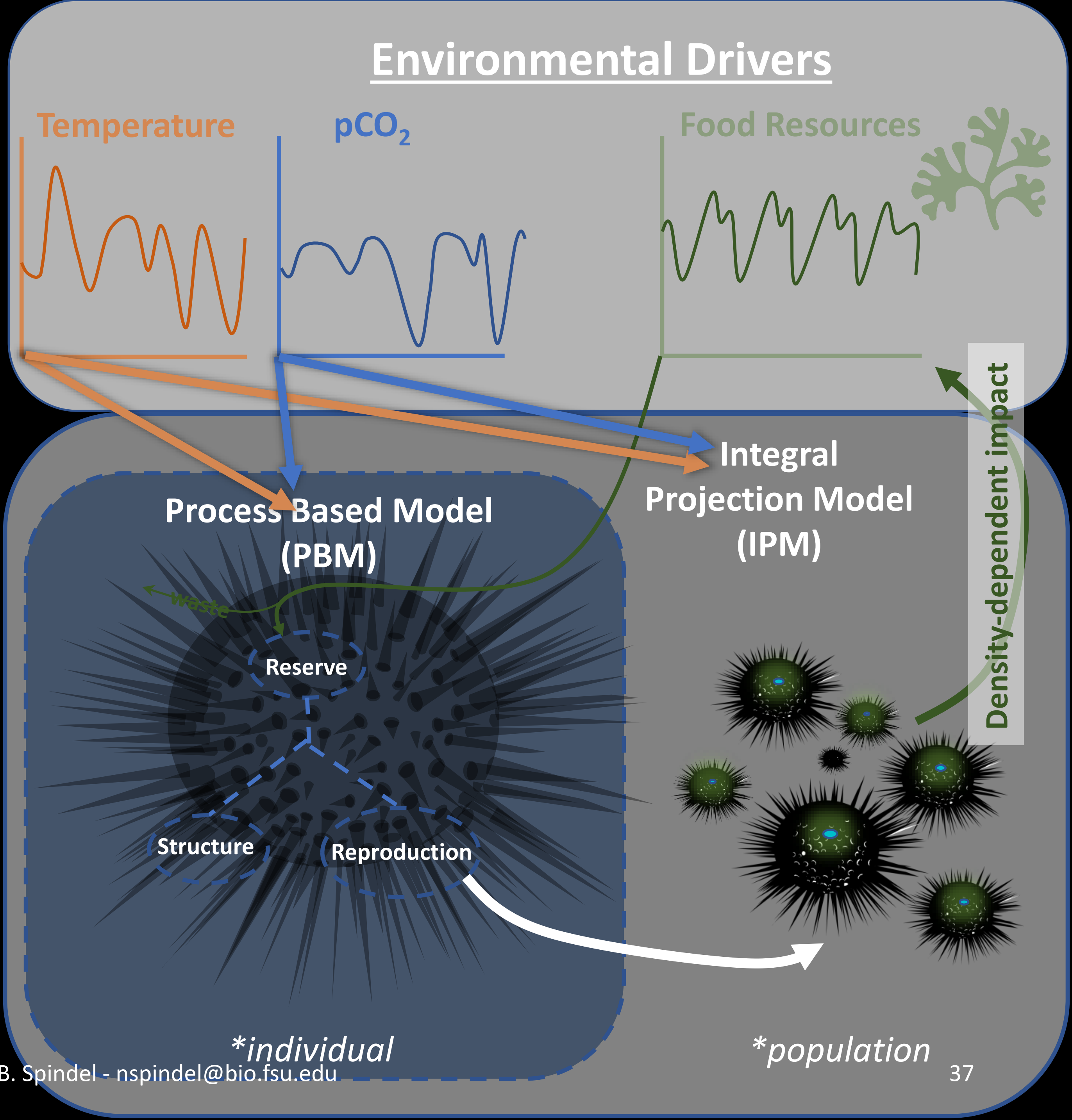
- ***Higher*** **metabolic rate in La Niña**


1200 µatm
600 µatm
Temperature (°C)
20.0
17.5
15.0
12.5
10.0
10
20
30
40
50
60
70
Test volume (mL)
0.2
0.6
1
1.4
1.8
2.2
gonad mass (g dry)
0.5
1.0
1.5
2.0

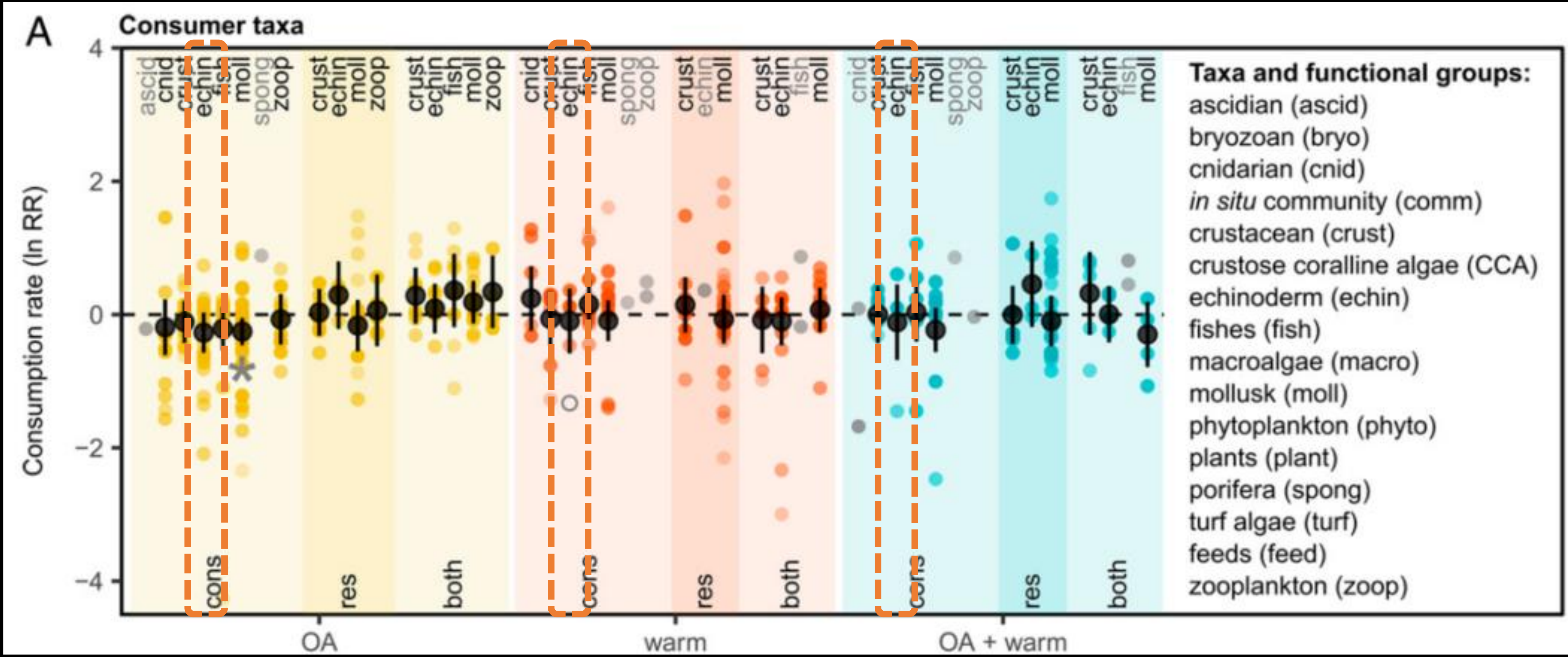

600 µatm
1200 µatm
Temperature (°C)
20.0
17.5
15.0
12.5
10.0
40
45
50
55
60
65
Test diameter (mm)
1.6
1.4
1.2
1
0.8
0.6
demipyramid growth (µm day⁻¹)
0.6
0.8
1.0
1.2
1.4
1.6

Process based model development for upscaling to population level herbivory

- ***Sensu*** **-** *Arnould-Pétré, M., Guillaumot, C., Danis, B., Féral, J.-P. & Saucède, T. 2021*



Kindinger, T. L., Toy, J. A. & Kroeker, K. J. 2022 *PNAS*



Stressors	Effect	Species	Study
Warming	**(+) disease & mortality**	*Tripneustes gratilla*	Brothers, C. J., Harianto, J., McClintock, J. B. & Byrne, M. 2016
		Holopneustes purpurascens & Heliocidaris erythrogramma	Sweet, M., Bulling, M. & Williamson, J. E. 2016
	(-) gonad development	*Paracentrotus lividus*	Shpigel, M., McBride, S. C., Marciano, S. & Lupatsch, I. 2004
		Echinometra sp.	Uthicke, S., Liddy, M., Nguyen, H. D. & Byrne, M. 2014
		Evechinus chloroticus	Delorme, N. J., Sewell, M. A. J. C. B. 2016
Acidification	**(-) body growth, (-) gonad growth, (-) calcification**	*Echinometra sp.*	Uthicke, S., Liddy, M., Nguyen, H. D. & Byrne, M. 2014
		Tripneustes gratilla	Byrne, M. et al. 2014
		Strongylocentrotus droebachiensis	Stumpp, M., Trübenbach, K., Brennecke, D., Hu, M. & Melzner, F. 2012
		Hemicentrotus pulcherrimus	Kurihara, H., Yin, R., Nishihara, G. N., Soyano, K. & Ishimatsu, A. 2013
	***high food may ameliorate**	*Amphibalanus (Balanus) improvisus*	Pansch, C., Schaub, I., Havenhand, J. & Wahl, M. 2014
Warming + Acidification	**(+) additive, metabolic rate**	*Echinometra sp.*	Uthicke, S., Liddy, M., Nguyen, H. D. & Byrne, M. 2014
		Heliocidaris erythrogramma (size range)	Carey, N., Harianto, J. & Byrne, M. 2016
	***+3℃ ameliorate negative effect of decreased pH (27-24 ℃, pH 7.6-8.2)**	*Tripneustes gratilla (larvae)*	Sheppard Brennand, H., Soars N., Dworjanyn, S.A., et al., 2010
		Tripneustes gratilla (adult)	Dworjanyn, S.A., Byrne, M., 2018

Literature Context

- OA + OW -> additive effect on RMR
  - Uthicke, S., Liddy, M., Nguyen, H. D. & Byrne, M. 2014 *Echinometra sp. A*
  - Carey, N., Harianto, J. & Byrne, M. 2016 *Heliocidaris erythrogramma*

- OA + OW -> +3℃ reduced the negative effect of decreased pH (27-24 ℃, pH 7.6-8.2)
  - Sheppard Brennand, H., Soars N., Dworjanyn, S.A., et al., 2010 *Tripneustes gratilla*
  - Dworjanyn, S.A., Byrne, M., 2018 *Tripneustes gratilla*

- Long-term warming -> impaired gonad development
  - *Paracentrotus lividus*,3 months; *Echinometra sp*., 2.5 months; *Evechinus chloroticus* 3 months
  - Shpigel, M., McBride, S. C., Marciano, S. & Lupatsch, I. 2004.
  - Delorme, N. J., Sewell, M. A. J. C. B., 2016

- OW -> increased disease & mortality
  - *Tripneustes gratilla* Brothers, C. J., Harianto, J., McClintock, J. B. & Byrne, M. 2016
  - Sweet, M., Bulling, M. & Williamson, J. E. 2016

- OA (pH 7.6) -> decreased body growth, gonad growth, calcification
  - Byrne, M. et al. 2014
  - Uthicke, S., Liddy, M., Nguyen, H. D. & Byrne, M. 2014
  - Stumpp, M., Trübenbach, K., Brennecke, D., Hu, M. & Melzner, F. 2012
  - Dubois, P. 2014
  - Kurihara, H., Yin, R., Nishihara, G. N., Soyano, K. & Ishimatsu, A. 2013
  - *high food conditions may ameliorate - Pansch, C., Schaub, I., Havenhand, J. & Wahl, M. 2014

1 Uthicke, S., Liddy, M., Nguyen, H. D. & Byrne, M. Interactive effects of near-future temperature increase and ocean acidification on physiology and gonad development in adult Pacific sea urchin, Echinometra sp. A. Coral Reefs 33, 831-845, doi:10.1007/s00338-014-1165-y (2014).

1 Delorme, N. J., Sewell, M. A. J. C. B., Molecular, P. P. A. & Physiology, I. Effects of warm acclimation on physiology and gonad development in the sea urchin Evechinus chloroticus. Comp Biochem Physiol A Mol Integr Physiol 198, 33-40, doi:10.1016/j.cbpa.2016.03.020 (2016).

1 Brothers, C. J., Harianto, J., McClintock, J. B. & Byrne, M. Sea urchins in a high-CO2 world: the influence of acclimation on the immune response to ocean warming and acidification. Proc Biol Sci 283, 20161501, doi:10.1098/rspb.2016.1501 (2016).

1 Kroeker, K. J. et al. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob Chang Biol 19, 1884-1896, doi:10.1111/gcb.12179 (2013).

1 Sweet, M., Bulling, M. & Williamson, J. E. New disease outbreak affects two dominant sea urchin species associated with Australian temperate reefs. Marine Ecology Progress Series 551, 171-183, doi:10.3354/meps11750 (2016)

1 Byrne, M. et al. Warming influences Mg2+ content, while warming and acidification influence calcification and test strength of a sea urchin. Environ Sci Technol 48, 12620-12627, doi:10.1021/es5017526 (2014).

1 Stumpp, M., Trübenbach, K., Brennecke, D., Hu, M. & Melzner, F. Resource allocation and extracellular acid–base sta in the sea urchin Strongylocentrotus droebachiensis in respon to CO2 induced seawater acidification. Aquatic Toxicology 110 194-207 (2012).

1 Dubois, P. The skeleton of postmetamorphic echinoderms in a changing world. Biol Bull 226, 223-236, doi:10.1086/BBLv226n3p223 (2014).

1 Kurihara, H., Yin, R., Nishihara, G. N., Soyano, K. & Ishimatsu, A. Effect of ocean acidification on growth, gonad development and physiology of the sea urchin Hemicentrotus pulcherrimus. Aquatic Biology 18, 281-292, doi:10.3354/ab00510 (2013).

1 Lewis, C. et al. Ocean acidification increases copper toxicity differentially in two key marine invertebrates with distinct acid-base responses. Sci Rep 6, 21554, doi:10.1038/srep21554 (2016).

1 Pansch, C., Schaub, I., Havenhand, J. & Wahl, M. Habitat traits and food availability determine the response of marine invertebrates to ocean acidification. Glob Chang Biol 20, 765-777, doi:10.1111/gcb.12478 (2014).

1 Collard, M., Dery, A., Dehairs, F. & Dubois, P. Euechinoidea and Cidaroidea respond differently to ocean acidification. Comp Biochem Physiol A Mol Integr Physiol 174, 45-55, doi:10.1016/j.cbpa.2014.04.011 (2014).

1 Collard, M. et al. Buffer capacity of the coelomic fluid in echinoderms. Comp Biochem Physiol A Mol Integr Physiol 166, 199-206, doi:10.1016/j.cbpa.2013.06.002 (2013).

1 Dupont, S., Ortega-Martinez, O. & Thorndyke, M. Impact of near-future ocean acidification on echinoderms. Ecotoxicology 19, 449-462, doi:10.1007/s10646-010-0463-6 (2010).

2 Dupont, S. & Thorndyke, M. Relationship between CO2-driven changes in extracellular acid-base balance and cellular immune response in two polar echinoderm species. Journal of Experimental Marine Biology and Ecology 424, 32-37, doi:10.1016/j.jembe.2012.05.007 (2012).

3 Dupont, S. & Thorndyke, M. Direct impacts of near-future ocean acidification on sea urchins. Climate change perspective from the Atlantic: past, present and future, 461-485 (2013).

1 Brown, M. B., Edwards, M. S. & Kim, K. Y. Effects of climate change on the physiology of giant kelp, Macrocystis pyrifera, and grazing by purple urchin, Strongylocentrotus purpuratus. Algae 29, 203-215, doi:10.4490/algae.2014.29.3.203 (2014).

1 Dupont, S., Dorey, N., Stumpp, M., Melzner, F. & Thorndyke, M. Long-term and trans-life-cycle effects of exposure to ocean acidification in the green sea urchin Strongylocentrotus droebachiensis. Marine Biology 160, 1835-1843, doi:10.1007/s00227-012-1921-x (2013).

1 Suckling, C. C. et al. Experimental influence of pH on the early life-stages of sea urchins II: increasing parental exposure times gives rise to different responses. Invertebrate Reproduction & Development 58, 161-175, doi:10.1080/07924259.2013.875951 (2014).

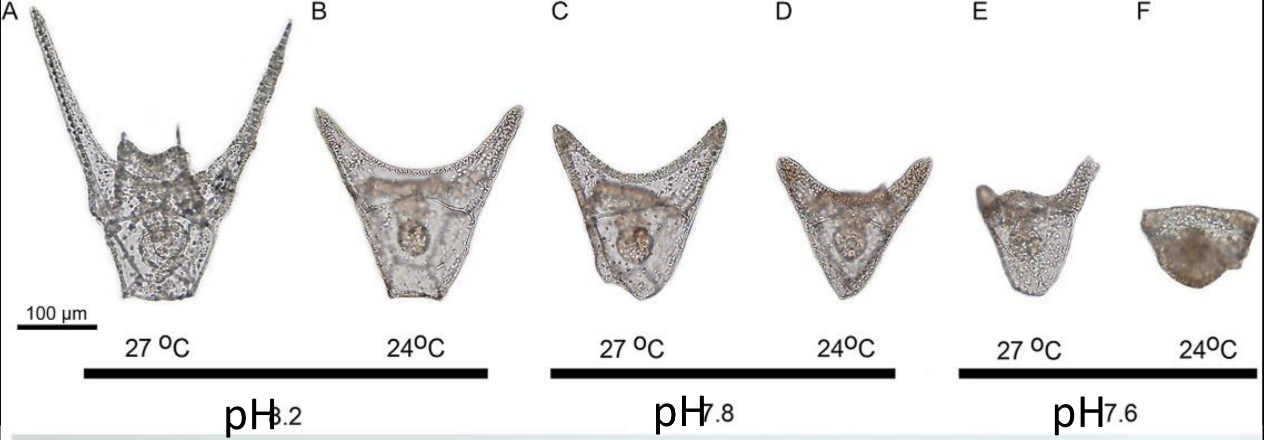
2 Suckling, C. C. et al. Adult acclimation to combined temperature and p H stressors significantly enhances reproductive outcomes compared to short-term exposures. Journal of Animal Ecology 84, 773-784 (2015).

1 Foo, S. A. & Byrne, M. Marine gametes in a changing ocean: Impacts of climate change stressors on fecundity and the egg. Mar Environ Res 128, 12-24, doi:10.1016/j.marenvres.2017.02.004 (2017).

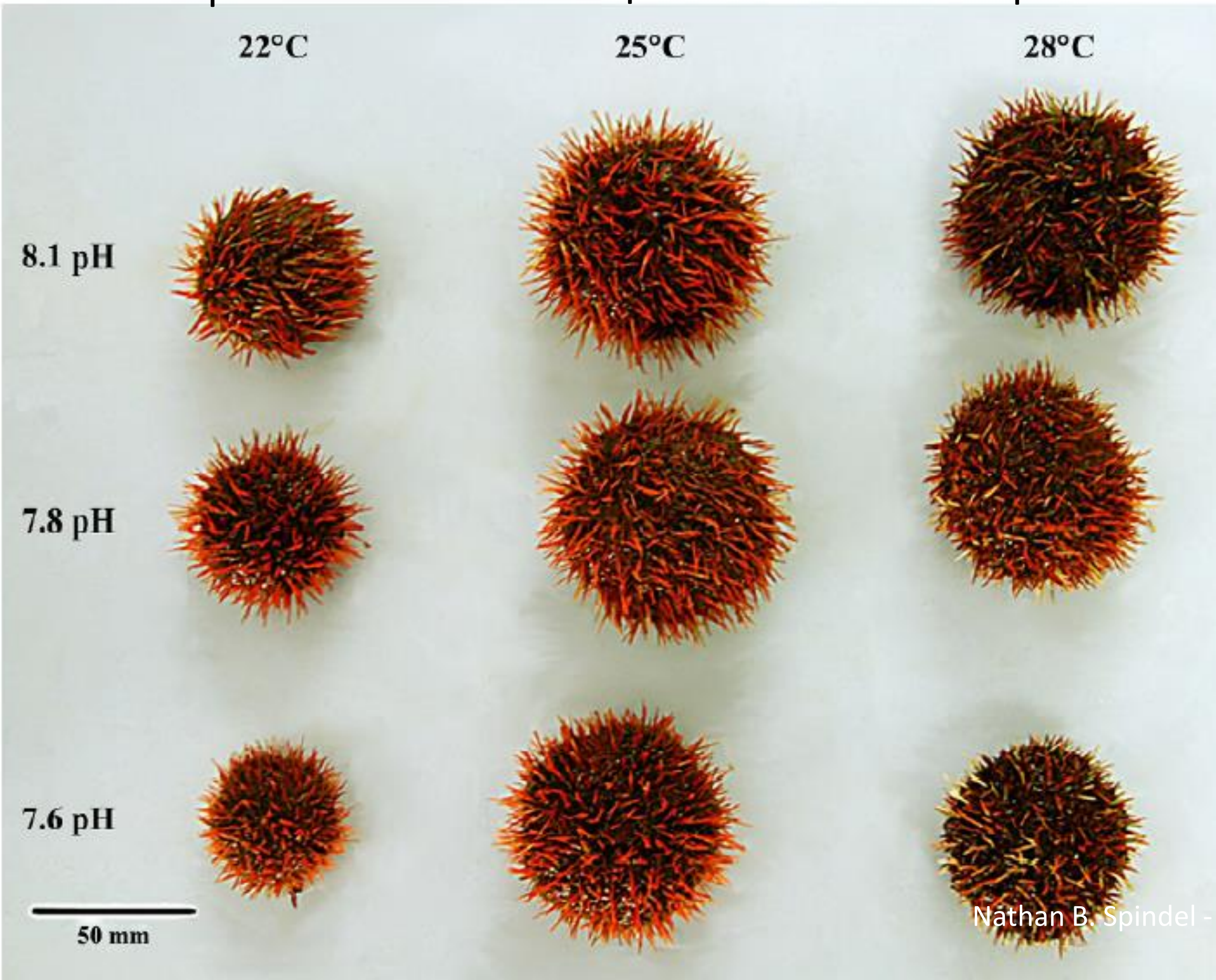
2 Foo, S. A., Byrne, M. & Gambi, M. C. Residing at low pH matters, resilience of the egg jelly coat of sea urchins living at a CO2 vent site. Marine Biology 165, 97, doi:ARTN 97 10.1007/s00227-018-3359-2 (2018).

1 Catarino, A. I., Bauwens, M. & Dubois, P. Acid-base balance and metabolic response of the sea urchin Paracentrotus lividus to different seawater pH and temperatures. Environ Sci Pollut Res Int 19, 2344-2353, doi:10.1007/s11356-012-0743-1 (2012).

1 Shpigel, M., McBride, S. C., Marciano, S. & Lupatsch, I. The effect of photoperiod and temperature on the reproduction of European sea urchin Paracentrotus lividus. Aquaculture 232, 343-355, doi:https://doi.org/10.1016/S0044-8486(03)00539-8 (2004).



Sheppard Brennand, H., Soars N., Dworjanyn, S.A., et al., 2010

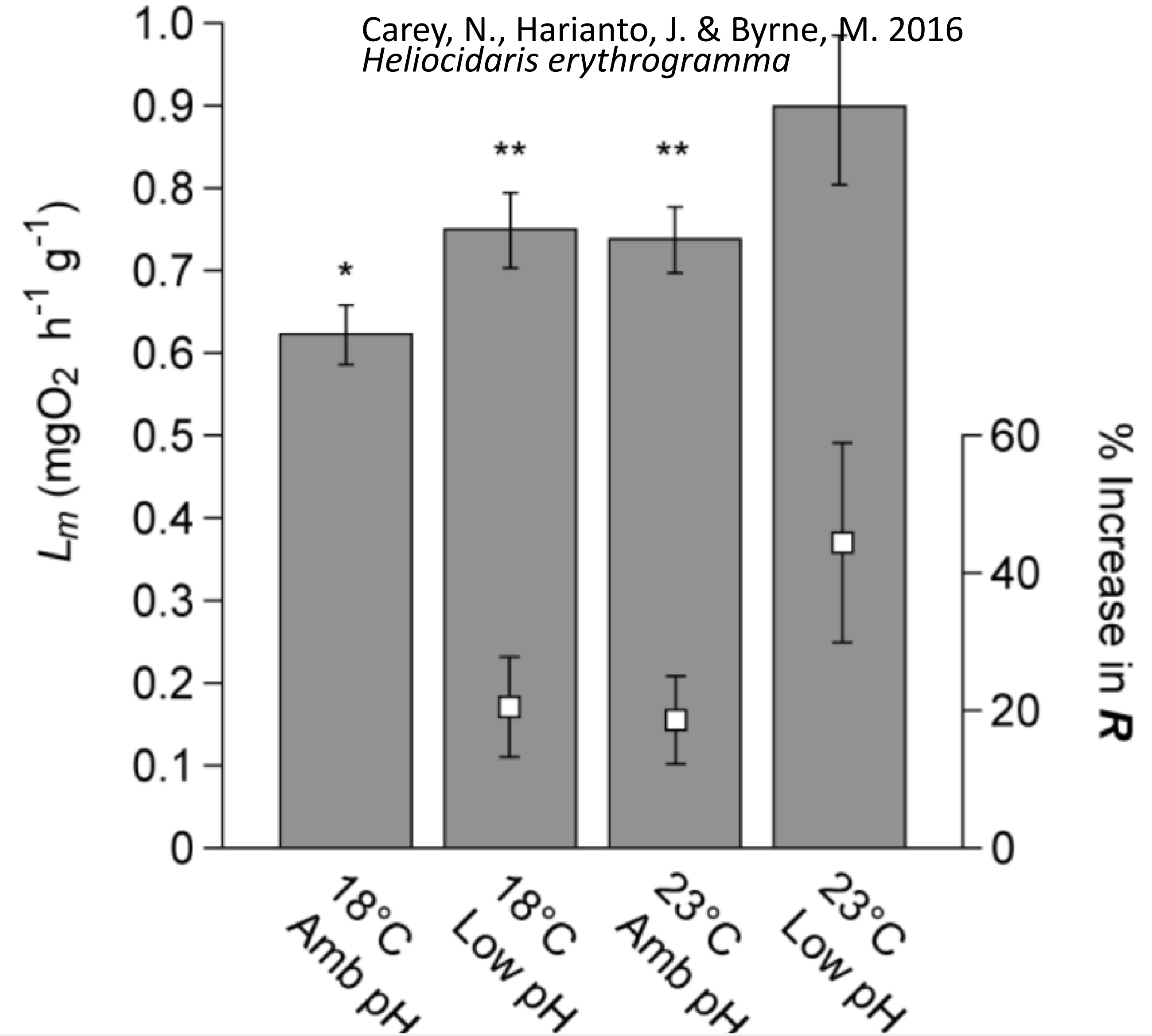


Multistressor effects – Combined warming and acidification

Tripneustes gratilla

+3°C reduced the negative effect of decreased pH

Dworjanyn, S.A., Byrne, M., 2018


Carey, N., Harianto, J. & Byrne, M. 2016
Heliocidaris erythrogramma
L_m (mgO$_2$ h^{-1} g^{-1})
% Increase in **R**
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
60
40
20
0
*
**
**
18°C Amb pH
18°C Low pH
23°C Amb pH
23°C Low pH

Uthicke, S., Liddy, M., Nguyen, H. D. & Byrne, M. 2014